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Recommended Bankfull Geometries For Flood Protection Channel Design, Upper Llagas Creek, Santa Clara County, California

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On behalf of the Santa Clara Valley Water District

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February 2012

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1. INTRODUCTION

1.1 Purpose

On behalf of the U.S. Army Corps of Engineers (Corps), the Santa Clara Valley Water District (SCVWD) is completing final design for the Upper Llagas Creek Flood Protection Project (Project) upstream of Buena Vista Avenue. The 61.7-square mile watershed includes much of the southern Santa Clara Valley and adjoining foothills of the Santa Cruz Mountains and Diablo Range, and inclusive of the urbanizing communities of Morgan Hill and San Martin. The design will be a partially naturalized design that includes an integrated approach to stable-channel design using established principles from several disciplines, including geomorphology.

"Bankfull" hydraulic geometry, which aims to quantify emulation of natural stable channels' channel-forming discharge, will be used to create recommendations for the configuration of the channels of Reaches 4, 5, 6, 7, 14 and the natural channel portions of Reach 8 (USACE, 2010). Calculations developed in this report will be used to guide channel geometry and placement of benches that act as floodplains within the larger conveyance channel.

1.2 Approach

Balance Hydrologics' (Balance) approach is based on development of a regional bankfull geometry curve that reflects field measurements of existing channel geometries in and near the Project areas. This new curve is compared to existing published curves for the larger Bay Area region.

Chapter 2 describes aspects of the study area affecting channel geometry, and how that geometry has been evolving in Llagas Creek. Methods of measuring and applying channel geometry are described in Chapter 3. We explain in Chapter 4 how regional data developed by the staffs of Balance, SCVWD, and other geomorphologists and engineers can be applied to develop criteria for channel design, and show the actual applications in Chapter 5. Chapter 6 discusses factors which modify our calculations. Our conclusions are summarized in Chapter 7, and Chapter 8 details study limitations.

1.3 Acknowledgments

This report includes substantial unpublished work by Liang Xu and other SCVWD staff (2009), by nine members of the Balance staff, and by Howell (2009)[1]. The sharing of this work, often the product of evening or weekend research, to develop Figures 6, 7, and 8 is both noteworthy and appreciated.

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[1] Howell's work was conducted at gaging stations, which typically are situated at locations particularly favorable for measuring streamflow, and by definition are not particularly representative of the stream channel. While we have no reason to question each individual point, we have not independently verified these results.

2. REGIONAL SETTING

Santa Clara Basin is nestled between the northwest-trending Santa Cruz Mountains and the San Andreas Fault to the west and the Diablo Range and the Hayward and Calaveras faults to the east. The Santa Clara Valley is a large trough that has been filled by sediment (gravel, sand, silt and clay) eroded from the adjacent mountain ranges. The Llagas Creek watershed collects water, sediment and other stream-borne materials primarily from the eastern flank of the Santa Cruz Mountains; Chesbro Reservoir impounds water, sediments, and wood from the upper western watershed (Figure 1). Small tributaries also emanate from the western side of the Diablo Range, joining the creek on the Santa Clara Valley floor. Llagas Creek is a tributary to the Pajaro River, which flows to the Pacific Ocean west of Watsonville, CA. The watershed of Llagas Creek at Buena Vista Avenue encompasses about a quarter of the catchment of Santa Clara Valley, which drains both to San Francisco Bay (Coyote Creek) and to the Pajaro River (Llagas and Uvas Creeks). The watershed at Buena Vista Avenue is about 5 percent of the 1300-square-mile Pajaro River drainage at its mouth.

2.1 Regional Geology and Soils

The geology of the project site and vicinity is shown on published U.S. Geological Survey maps by Dibblee (1973a,b), Helley and others (1979), McLaughlin and others (2001), on a published California Division of Mines and Geology map by Rogers and Williams (1974), and on various other references listed at the end of this report. Knudsen and others (2000) have refined the depiction of surficial geology of the San Francisco Bay Region, including Santa Clara County, by mapping the distribution of late-Pleistocene to recent geologic units and their relative susceptibility to liquefaction. These maps articulate the relationship between younger Pleistocene and Holocene alluvial deposits left by the modern channel system and older deposits related to alluvial fans from the Diablo drainages to the east that frame the Llagas Creek channel. A depiction of the sequence of deposits exposed in the bed and banks of the channel is mapped by Peters and others (2003).

2.2 Local Geology and Soils

There are several notable existing conditions in the watershed, which inform historical channel evolution, and should be acknowledged as antecedent conditions. These conditions, which can impact channel design, can be summarized as:

- Little Llagas Creek arcs around the western edge of an ancient alluvial fan derived from the ancestral Coyote Creek drainage system, which has flowed south to the Pajaro system at various points in the geologic past (c.f., Iwamura, 1995; Foster and Hecht, 1999). Bank composition and channel substrate change along the length of the Upper (and Lower) Llagas Creek system in correspondence with proximity to either Pleistocene ("glacial-age") alluvial fan deposits or more clay-rich deposits associated with distal portions of fans, lobes, and alluvium deposited by other channels draining the valley floor and slopes.

- Southward from Church Avenue, and particularly southward from Buena Vista Avenue, portions of the sediments underlying the valley and forming the banks of Llagas Creek are composed of Pleistocene lake and marshy lake-marginal deposits which periodically formed as the Pajaro River narrows at Chittenden were recurrently dammed by movement along the San Andreas Fault. Jenkins (1973) describes this process, and most particularly the muddy deposits left by the two most recent Pleistocene lakes -- Lakes San Benito and San Juan -- which formed in the southern Santa Clara Valley tens of thousands of years ago. The lakes have left deposits of heavy lacustrine clay and silt – progressively thickening southward to the Bolsa plain south of Gilroy -- that have direct bearing on regional groundwater hydrology, and presumably on channel dynamics where interaction occurs between the active channel and the elevations of these deposits. Lake San Benito briefly flooded much of the Llagas Creek valley system, leaving high-stand deposits at the 400-foot elevation contour, while, more recently, Lake San Juan persisted at the 200-foot elevation contour. Many of the irregularly-distributed cohesive soils along the stream likely result, directly or indirectly, from development on lake deposits.

- The Eastern Santa Clara Area Soil Survey (Lindsey, 1974) describes soils data within the project boundaries (and elsewhere). These data show clearly a soil catena that demonstrates a heritage based on the ancestral Coyote Creek alluvial fan complex mixed with a present-day reworking of these fan deposits along with the formation of natural levee deposits and other ephemeral wetland deposits (the Laguna Seca area to the immediate north of Morgan Hill). Arbuckle, Yolo, Cortina, and Garretson soils tend to be more friable and coarse, while Pleasanton, Zamora, Cropley, and San Ysidro soils tend to have higher clay content (possibly with claypans or other old soil horizons in which clays have accumulated over the years), which equates to less erosivity and steeper stable banks.

2.3 A History of Channel Incision

Large channel or watershed disturbances, such as land-use changes, regulation, channelization, earthquakes, wildfires, or atypical floods, can alter equilibrium conditions in a watershed. All of these perturbations play a part in the variation of a natural sediment supply (see Leopold and others, 1964; Hecht, 1993). Much of that supply originates from upper watersheds as coarse materials that contribute mineral components for soil during breakdown. These sediments are a necessary component of healthy stream channels and the surrounding floodplains. Over the past decades, sediment delivery to the channel may well have slowed for a variety of reasons including the building of Chesbro Reservoir. Reduced delivery of coarse sediments is one cause of potential channel instability and incision.

Llagas Creek watershed has a history of channel incision dating back to 1915 (Noble and NWH, 2008), and likely earlier. Conversion of the oak savanna of the Santa Clara Valley to agriculture during the early years of the Gold Rush increased the number of ditches and connections between the mountains and the axial valley streams such as Llagas Creek, and likely contributed to the beginning of channel incision (Grossinger and others, 2008). Channel incision probably resulted from efforts to 'improve drainage', from narrowing of channels at bridge crossings, and from active channel deepening as a means of flood control.

The loss of natural water and sediment supplies can lead to substantial changes in the character of downstream channels; channel incision is often a consequence. Chesbro Reservoir was built in the upper Llagas watershed in 1955. It impounds water and sediments from the portion of the watershed with the highest precipitation. Llagas Creek is a regulated system, with a significant change in the amount of water and sediments that are available to the channel network downstream of the dam. While regulation contributes to incision, it is not the only driver of channel instability.

In addition to regulation, downstream withdrawals of water from the channel itself as well as from local wells can affect stream conditions. Changes in land use such as conversion of lands to agriculture and an increase in impervious surfaces due to urbanization often lead to channelization, which can accelerate channel adjustments like downcutting, loss of habitat, and stagnation. Flood protection measures, which in previous decades often involved channelization, are another source of channel degradation that can cause incision. The cumulative effects of decades of changes in land use, the increase in impervious surfaces, flood protection measures, sediment supply loss, water diversions, hydrograph modifications, and channelization create significant issues for any watershed.

Incised channels are not stable because of bank over-steepening and channel confinement, which create the potential for bank erosion and mass failures during heavy rains or high runoff. This feedback loop can result in deep and wide channels; as the channel incises, banks fail, which creates a wider channel, and then a 'new' incised channel and tributary gullies develop as the channel tries to adjust to the changed condition.

channel and its floodplain (USGS, 2004). The perpendicular distance between the average channel bed elevation and the floodplain is the *bankfull depth.* The distance between an inflection point on one side of the channel to the inflection point on the other side of a channel at the floodplain elevation is the *bankfull width.* Bankfull width points should be generally equivalent in elevational position on each bank. Depth and width measures are used to calculate *bankfull cross-sectional area* at specific cross-sections (Figure 2), which are then averaged among cross-sections for reach-averaged metrics. If stage-discharge relations or velocities during a bankfull flow are known, *bankfull discharge* can also be calculated. Bankfull depth, width, cross-sectional area, and discharge have been found to be highly correlated to the size of the watershed (drainage area) across a given region (c.f., Dunne and Leopold, 1978).

3.2 Applications

The analyses and recommendations provided in this report are refined guidance on the bankfull channel design of Llagas Creek such that the project tenant of geomorphic stability is met. Preliminary qualitative design considerations were developed at the reach scale based on geomorphic inference, local geology and soils, and preliminary Corps designs and the updated design concept (Strudley and Hecht, 2010). Those initial qualitative suggestions have been enhanced with quantitative recommendations by considering the results of our bankfull geometry analyses. The updated concept developed by the RMC Water and Environment consultant team, including Balance, incorporates a low floodplain, as well as slopes suitable for plant and tree preservation, restoration, and rehabilitation. This report's intention is to provide specific guidelines that incorporate the myriad quantitative *and* qualitative considerations necessary to achieve a more stable channel design. Below are the qualitative recommendations for channel design guidance (Strudley and Hecht, 2010), which should be used in concert with the new quantitative data presented in Chapter 5.

- Where possible, channel banks should be relaxed landward of a point bar, or on the inside of channel bends. These channel areas often exhibit more relaxed topography, and are typically sites where channels tend to deposit sediment. Meandering and point-bar development is more pronounced in the lower-most Reaches (Reaches 4 and 5 and lower Reach 6). It would be geomorphically preferable to place low floodplains and bank relaxation on alternate sides depending on channel structure along the length of the lower Reaches.

- Where possible, channel banks should be relaxed where soils are more friable, coarse, and less stable. Soils that are more clay rich, or that have claypans or incipient duripans, will tend to act more reliably as steeper cut banks (outside of bends), while the more loose (friable) soils will be more suitable for bank relaxation and floodplain placement. Drainage on these soils will be better, in general. In prior work (Strudley and Hecht, 2010), we used the Eastern Santa Clara Area Soil Survey (Lindsey, 1974) as an overlay on the aerial imagery of the lower Reaches to approximate locations of friable versus more durable soils. Arbuckle, Yolo, Cortina, and Garretson soils tend to be more friable and coarse, while Pleasanton, Zamora, Cropley, and San Ysidro soils tend to have higher clay content (possibly with claypans), which equates to less erosivity and steeper stable banks.

- If possible, channel banks should be relaxed opposite the sides where tributary channels join the main stem channel. Tributaries deliver flood waters and sediment, and wider channel geometry opposite such confluences affords accommodation space and temporary storage for the flux of water and sediment. Tributary channels enter the lower Reaches from the east (San Martin Creek, Church Creek) in Reach 14. Thus, the western (right) bank side in Reach 14 would be a more geomorphically preferable selection for bank relaxation.

- As a general rule, channel widening should occur at meander bends, with the width increased and bank slope relaxed on the inside of the bend (point bar). It may also be appropriate to increase the meander wavelength and/ or amplitude to afford more hydrodynamic energy dissipation. This will tend to induce temporary storage of sediment in point bars while decreasing erosive force throughout the Reaches where this is employed. Conversely, channels tend to be more tolerant of narrowing (all other factors being equal) at the inflection points or 'crossovers' between meander bends.

Natural channels are generally sinuous in nature, and often tend to develop curves approximately proportionate to the size of the channel. Empirical studies have revealed linear relationships between channel width and meander wavelength and radius of curvature for channels in alluvial valleys. Meander wavelengths range from 7 to 10 channel widths, with meander inflection points spaced about 5 to 7 channel widths measured along the channel. Values reported for the ratio of radii of curvature to width range from approximately 1.5 to 4.3, with a median of 2.7 (Leopold, Wolman, and Miller, 1964). Sinuous planform geometry is typically described by the dimensions of meander wavelength, meander amplitude, and radius of curvature (Figure 3).

An in-depth discussion of the relationship in Llagas Creek between the radius of curvature, meander amplitude, channel width and other parameters was provided in an additional memorandum using metrics described by USACE engineers (1994a,b); Leopold, Wolman, and Miller (1964) and other geomorphic researchers, so that a more thorough understanding of meander geometry is achieved before new-channel-section meander designs become finalized (Senter and Hecht, 2011).

3.3 Bankfull in Incising Channels

Factors influencing channel incision were explored during the channel design phase for the project Reaches. As noted in Section 2.3, Llagas Creek has measurably incised 12 to 20 feet below the adjacent floodplain elevation (Figure 4, from Noble and NWC, 2008); in most cases, flow and deposition during recurrence events not much greater than a 2 year flow (e.g. a 5-year flow event) are now disconnected from the valley floor. Alluvial terraces, generally narrow, have formed within the incised channel, but do not serve the same functions as the formerly wide floodplain. When a channel is connected to its floodplain, stream energy is released during high flows as the wetted channel width expands onto the floodplain, which helps to attenuate flooding. Further, as energy is dissipated, fine sediments settle out of the water column on the floodplains, which in turn builds, strengthens, and stabilizes bank conditions.

It can be difficult to measure bankfull geometries in incised channels because bankfull by definition should fill the available channel completely. A discharge that was once visibly bankfull will now stay well within the adjusted, incised channel dimensions. This condition is evident in Llagas Creek at Buena Vista Bridge, which is the site of Balance's stream gaging and sediment-transport monitoring performed in conjunction with the ongoing Project (Figure 5, Strudley and others, 2011). Figure 5 shows current channel incision and today's bankfull overflow condition at flows which were perhaps greater than a 2-year return interval event (more likely on the order of a 5-year event).

The field-based method to figure out what bankfull might be for a reach of interest is to visit nearby reaches where historic channel conditions were similar, and where current conditions are less incised (or otherwise disturbed) than those at the reach under study. This type of analogue is called a reference reach, which can serve as equivalent but less-altered channels so that conditions at a study site can be inferred. Tables 1 and 2 contain channel geometries of less-altered channels; those enclosed in parentheses indicate that measurements are from regulated systems, which are more likely to be incised than the other measurements.

4. REGIONAL MEASUREMENTS

Dunne and Leopold published average bankfull geometry values of width, depth, and area as a function of drainage area for the San Francisco Bay Region on log-log plots (Figures 6-8) in their seminal text, Water in Environmental Planning (1978, p. 615). Riley (2003 and earlier work) developed another set of *eastern* San Francisco Bay Region regression curves for cross-sectional area (Figure 6) from subsequent work performed largely in Alameda and Contra Costa Counties. The result of the Riley regression positioned below the Dunne and Leopold regression is, in part, an indication of climate, in particular the differences in precipitation and subsequent runoff when comparing mainly North Bay locations (Dunne and Leopold 1978) and East Bay locations (Riley 2003). The following sections explain the development of another set of bankfull geometry curves that are more specific to the inland regions of Southern Santa Clara County and Monterey Bay County.

4.1 Criteria for Selecting Sites

An Inland South Bay and Monterey Bay Region curve was built from bankfull geometry measurements collected by Balance staff and others over the course of years during many geomorphic projects conducted in the region. The criteria for data inclusion were a) proximity to Upper Llagas Creek, with b) similar climate, and c) measurements taken from sufficiently natural channels. These criteria restricted data mining to measurements taken in Santa Cruz Mountains streams, Santa Clara Valley streams, the Pajaro River system, inland Monterey Bay Coast Range streams, and other drainages in lower precipitation rural fringes of the Santa Cruz Mountains. Only the most relevant of these data were subsequently used to develop new Inland South Bay and Monterey Bay regional curves.

4.2 Regional Curve Development

Regional hydraulic geometry relations were developed based on local creeks with similar loamy soils, relief, climate and hydrology to that of upper Llagas Creek. We used data from Balance's work and others (Howell, 2009) as well as from the Santa Clara Valley Water District (Xu and others, 2009).

The bankfull geometry regressions of Dunne and Leopold (1978) and Riley (2003) are generally applicable across the entire San Francisco Bay Region, and with higher confidence in the regions specified by their authors. Dunne and Leopold (1978) called them 'San Francisco Bay region at 30" annual precipitation' while Riley's curve is entitled 'Adjusted Regional Curve for the East San Francisco Bay Region'. The Dunne and Leopold and Riley regressions served as baseline data, and the selected inland South Bay and Monterey Bay data were graphed alongside them. Regressions were then developed specifically to derive new Inland South Bay and Monterey Bay regional curves (Figures 6-8, Tables 1-2).

The new cross-sectional and width regressions are derived directly from the plotted data, whereas the depth regression equation was modified to reflect the parallel step-down pattern seen between the Dunne and Leopold curve and the Riley curve (Figure 6). The parallel step-down pattern of the cross-sectional area regression for the San Francisco Bay region at 30"

3. BANKFULL GEOMETRY OF SELF-FORMING CHANNELS

Bankfull geometries can be used to design new channel configurations based on the relationship between channel dimensions and the water surface elevation during a 'typical' flood event. A typical flood event has a statistical recurrence interval of approximately every 1.0 to 2.2 years (Dunne and Leopold, 1978). Most commonly, a bankfull return interval is approximated as a 1.5 to 2-year return flood. Bankfull events happen when flowing water fills the channel completely to the level of the floodplain in a channel that has not been incised due to human activities. The associated discharge for a bankfull flow is called *bankfull discharge*. Bankfull discharge is differentiated from *effective discharge*, which is defined as the flow that, statistically, is most efficient in moving the natural sediment load through the channel. This metric is calculated using flow duration and sediment transport curves. Both metrics are said to maintain the morphological and ecological health of a channel.

3.1 Magnitude and Frequency

In order to understand the concepts behind *bankfull discharge* and the associated *channel geometry*, it is useful to think of the importance of dynamic equilibrium in a stream channel. Dynamic equilibrium is predicated by climate, geology, and topography; three dominant variables in the erosion process. Stream channels carry and deposit eroded sediments depending upon how much water is flowing through the system (discharge), the shape of the channel itself (geometry), and the size and amount of sediment available to a channel. Stream channels are self-formed in a dynamic fashion by the fluctuating state of these components. These fluctuations are often not noticeable until a storm generates a large enough runoff event—and thus enough discharge and sediment—to create conspicuous changes to the channel. These changes may be erosional or depositional in nature, and vary in space as well as time. Theoretically, a channel is in dynamic equilibrium when over some long-term length of time the discharge in a watershed efficiently carries the available sediment out of the system (Morisawa, 1968; Riley, 2003). Put another way, a "graded stream", or quasi-equilibrium channel, maintains a consistent width and depth over time as it transports only the sediment delivered to or through it, no more, and no less.[2] Channel geometry analysis quantifies these consistent widths and depths of the channel, and how it varies along a channel.

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[2] We would like to stress at this point in this theoretical discussion that most, if not all, geomorphologists hold the notion of a "graded stream" as a theoretical construct only, and not a completely realizable situation in any natural setting. As such, our results and discussion that follow are based within this context—the cross sectional design geometries presented can only behave under equilibrium conditions if boundary conditions and probabilistic forcing conditions are not changed drastically. Large channel or

3.1.1 Theory

Channel geometry is used to describe the physical size, shape, and characteristics of a channel in relation to stream discharge, and is similar for channels of the same size in comparable climates (c.f., Dunne and Leopold, 1978). Precipitation and runoff can vary significantly at all timescales, yet average conditions exist for every geographical area. Natural, self-formed channels are sustained by its flows, but channel size is not typically large enough to convey larger than average, yet fairly frequent, discharge events. When not bound by bedrock or steeply incised banks, these moderate flood flows overtop channel banks regularly. The floodplain – the part of a river corridor that activates when flows go overbank during high water – is inundated during these flows. In terms of channel-sustaining flows, very large flood events are not frequent enough to be the primary force for maintenance of channel characteristics, although very large channel changes can be generated at time of occurrence (Dunne and Leopold, 1978).

3.1.2 Bankfull in the field

Figuring out what flow constitutes a bankfull discharge can be a difficult task. It becomes even more difficult with changes in peak flows, sediment supply, or flood routing. A flood-frequency analysis, if enough flow records are available, is often used as an initial estimator of bankfull discharge using a flow-return interval of ~1.0–2.2 years (Dunne and Leopold, 1978), and generally between 1.5 and 2 years (Leopold and others, 1964; Riley, 2003). Field measures of *bankfull geometry* is the preferred approach to identifying bankfull discharge, although flood-frequency analyses (which typically assume that bankfull discharge is equivalent to the peak 2-year flood) are used as a proxy, either as a convenient engineering shorthand or where rapid incision precludes field identification of the "morphological" bankfull level.

Bankfull geometry can be best measured in the field by selecting a representative stream reach with few to no obstructions, then establishing enough cross-sections in the representative reach to reasonably represent the range of local channel conditions. For instance, if a selected 100' reach has a pool (slow and deep flow) and a riffle (shallow and fast flow), a minimum of two cross-sections should be established to capture both conditions. Physical observations along a cross-section are used to identify, if possible, an inflection point on both banks between the

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system disturbances, such as earthquakes, wildfires, or atypical floods, can alter equilibrium conditions over the shorter term (c.f., Hecht, 1993); tectonic uplift, climate or vegetational changes can result in longer-term changes over periods of hundreds or thousands of years. Recognizing and interpreting episodic disturbance is critical to interpreting hydraulic geometry, and should be done by trained, registered personnel. One of the reasons why width proves to be a more predictive measure than depth, as we shall see later in this report, is that depth changes more quickly in response to episodic events, and may not always be in dynamic equilibrium.

annual precipitation curve and the Adjusted Regional Curve for the East San Francisco Bay Region curves show Riley's (2003) curve plotting lower. This result derives from the differences in regional rainfall-runoff rates in a southerly direction and thus in channel geometry, as smaller channel form with less runoff. The width curve for the new Inland region reflected this same parallel pattern, whereas the depth curve did not. The adjustment to the depth curve for the Inland South Bay and Monterey Bay region was justified after considering that channel geometries are inextricably linked, representing a condition that should be proportional across parameters (i.e. area = width * depth). Balance suggests that this proportionality should be reflected in the average (regression) condition rather than allowing outliers in one dimension (depth) to greatly influence an equation. Prior to the adjustment, the depth regression curve was steeper, with an approximate 5% slope. In comparison, the adjusted curve regression and accompanying equation that are shown in Figure 8 have a slope of 1.8%. To make this regression adjustment, two data points, (which continue to be visible on Figure 8) were *not* plotted: Llagas Creek at the downstream end of Reach 5 and Llagas Creek at Buena Vista Reach 6, as channel depths at these two locations were much greater than at any other location due to atypical local conditions (discussed below).

The finalized regression equations were utilized in Chapter 5 to derive Llagas Creek channel geometry designs, and are presented as design parameters (Table 3) along with the existing San Francisco Bay Region equations for comparison. Also included in Table 3 are equations for bankfull discharge (see upcoming Chapter 4.5.1), meander wave length, meander amplitude, and radius of curvature (see Figure 3 for visual context).

The newly developed Inland South Bay and Monterey Bay regression equation for bankfull cross-sectional area (Figure 6) is:

$$y = 10.95x^{0.68} \qquad (3),$$

for bankfull width (Figure 7) is:

$$y = 11.80x^{0.31} \qquad (4),$$

and for bankfull depth (Figure 8) is:

$$y = 0.98x^{0.28} \qquad (5).$$

4.3 Discriminating East and West Santa Cruz Mountain Curves

In all mountain systems, the orographic effect plays a primary role in the amount and type of precipitation that falls in a particular geographic location. As storm systems approach the Santa Cruz Mountains from the Pacific Ocean, air masses are forced to rise in order to get over the mountains. Differences in the amount, intensity and frequency of rainfall between the eastern and western sides of the Santa Cruz Mountains are sufficient such that their channels have distinct geometries (see Tables 1 and 2).

Llagas Creek is an eastern Santa Cruz Mountain stream in the Santa Clara Valley. All of the selected channel geometry data used to develop the Inland South Bay and Monterey Bay regional curves are from the Santa Clara Valley and the inland side of the Coast Ranges in Monterey County. No channel geometry data were used from the western slope because rainfall amounts are significantly higher, and storm tracks and watershed conditions differ.

4.4 Field Verification

Bankfull geometry measurements were collected in the field at the confluence of Llagas Creek Reaches 5 and 14. These measures helped to understand some of the current conditions at two project reaches (Table 1). Other local channel conditions in Table 1 can be considered as coming from reference reaches, where measurements in channels with less historical manipulation were collected. Realistically, most channels in the region have some amount of manipulation. The regression equations in Figures 6 to 8 reflect average conditions from these reaches as well as from some of the Llagas Reaches. This melding of incised and less-incised channel geometry measurements used to arrive at recommendations recognizes actual conditions in Llagas Creek (Figure 9) as well as conditions that are more reflective of natural geometries for the region. Bankfull area and widths plotted as expected (i.e. parallel to and lower than the other curves), suggesting adequate representation of natural channel conditions. The adjustment of the bankfull depth regression, on the other hand, is another indication that Llagas Creek is incised.

4.5 Discussion

Our analysis shows that rainfall, regulation, and regionalization all substantially affect hydraulic geometries and bankfull relationships which we may use to recommend sizes for Upper Llagas Creek Project Reaches. The following sections discuss these influences, and how they led to our choices in values to recommend. The final section focuses on the value of flexibility in selecting the values for design.

4.5.1 Rainfall

With a mean annual rainfall of about 18-24 inches, the Llagas watershed upstream of Buena Vista Avenue is substantially drier than the 30-inch rainfall watersheds used by Dunne and Leopold (1978), and the 25- to 30-inch rainfall zone of the Riley (2003) curve. Balance used the upper mean value of 24 inches in our calculations involving precipitation. In natural channels, the bankfull width, depth and cross-sectional area should be lower for channels with more runoff than those with less runoff.

Rantz (1971) developed well-documented regression equations to estimate the 2-, 5-, 10-, 25-, and 50-year peak flows as a function of precipitation and drainage-basin size for non-urbanized watersheds in the 10-county Bay Area.

The equation for Rantz' (1971) 2-year recurrence event in non-urbanized watersheds is:

$$Q_{p2} = 0.069A^{0.913}P^{1.965} \qquad (6),$$

where A is drainage area (square miles) and P is mean annual rainfall (inches). With an exponent of 1.965, a doubling of rainfall can increase peak flows by a factor of nearly 4. Hence, rainfall is a major factor in the size of a stream's bankfull channel.

The development of new Inland South Bay and Monterey Bay regional curves allow for a better estimation of geomorphically stable channels for rainfall anticipated within the Project area. The use of the conventional regional curves by Dunne and Leopold and by Riley would lead to a substantial over-estimate in bankfull geometry because of higher rainfall averages.

4.5.2 Existing and design flows

USACE hydrology data for exceedance probability flows that apply to reach sub-sections and other project aspects (Table 5, USACE 2010) are the basis of the Project designs. USACE (2010) reports discharge values as exceedance probabilities. These can be transformed into a return interval by simple division of 1/ exceedance probability, which for the case of 50% exceedance probability would calculate as: 1/ 0.5 = 2. The values associated with USACE 50% exceedance probabilities, then, should be approximately equivalent to Rantz' (1971) 2-year return interval regression based on area and mean annual precipitation (Equation 6) and possibly including urbanization effects.

According to Rantz (1971), a completely urbanized basin in the San Francisco Bay region could have 2-year peak flows that are 4-times the 2-year peak flows in a non-urbanized basin. Table 4 shows that the Corps discharges are substantially higher than those predicted by Rantz (1971). Thus, the question of urbanization must be discussed, as it is well documented that urbanization increases peak discharges. An urbanization ratio from Rantz (1971) is available for use. As an example of urbanization effects, Rantz' (1971) ratio of flood-peak magnitude for urbanized basins shows that for an urbanized basin with 60% channelization and 60% developed land, a multiplier of 2.25 should be applied to equation (6) for a 2-year predicted flow event (Table 4). In Reaches 7, 8, and 14 the USACE 50% exceedance flow projections are greater than the 60% urbanized and 60% channelized flow derived from Rantz (1971). This difference could widen or narrow depending on actual channelization and developed land values. For Reaches 4, 5, and 6 the USACE predicted flows were closer to the non-urbanized flows, which suggests that urbanization/ channelization effects may not be as impacted due to the dominantly rural local landscape; thus, urbanized values for these Reaches are not included in Table 4.

The computational methodology used by USACE (2010) to assess Llagas Creek watershed hydrology is significantly different from the statistical relationships developed by Rantz (1971) and applied here. The report states that urbanization projections to 2050 were taken into account, which may partially explain the high values when compared to Balance's 'geomorphological context' discharge calculations using Rantz (1971) non-urbanized conditions (Table 4). In order to correlate the Corps 2-year flow with Balance's geomorphological flow, it may be important to understand what levels of urbanization were applied to the USACE data, but that information is not available. Comparison of the USACE flows to the Rantz (1971) flows allows additional confidence when selecting either the urbanized or non-urbanized Rantz (1971) flows as the Project bankfull discharge flows.

Stage-discharge or flow frequency relations for the Upper Llagas Creek mainstem would serve as another line of evidence for the development of the regional curves, but one is not currently available. The relations used by USACE (2010, p. 16) are not appropriate for this discussion due to the location of the stream gages (above and directly below Chesbro reservoir), the small watershed area to which those curves apply (9.63 mi^2 and 19.6 mi^2, respectively) and the large impact of reservoir operations. USACE (2010) used data from the USGS gage 11153470 Llagas Creek above Chesbro Reservoir, near Morgan Hill, CA, which gages flow on its way to Chesbro Reservoir. The USGS gage 11153500 Llagas Creek near Morgan Hill, CA, gages flow directly below the reservoir, including flow from the reservoir itself. Both gages are impacted by reservoir operations and have limited data available for use: 11153470 collected data 1971-1982 and 2003-present, while 11153500 collected data 1951-1971.

A stage-discharge relationship was developed on Llagas Creek at Buena Vista Avenue Bridge by Balance over the period of one water year (WY), from October 1, 2010 through September 30, 2011 (Strudley and others, 2011). The data are valuable for constraining bankfull geometry recommendations, for comparing to estimates of effective discharge, and in developing the sediment rating curves which in turn are essential for calculating realistic effective discharges to be used in the USACE-developed SAM model for the low flow channel design component of this Project.

Figure 5 shows a 508 cfs flow condition at the Buena Vista Bridge at 14:15 during the March 24, 2011 site visit, on the rising limb of the hydrograph. This figure shows that flows were beginning to overflow the channel (thus representing bankfull conditions in an incised channel) 8 hours before the peak flow of the event, which was 2765 cfs at 22:30. The rectangular channel, as seen in the dry-condition photo, was conveying ~50 cfs of flow as seen in the bankfull-condition photo. These photos show that flows would not spill to the floodplain in a 'normal' bankfull event (~2-yr discharge).

4.5.3 Regulation and impoundment

Streams with mid-drainage reservoirs or other impoundments have smaller bankfull dimensions than non-regulated basins of similar size, because dam releases attenuate flow peaks. Llagas Creek, which is regulated by the relatively large mid-drainage Chesbro Reservoir, might be expected to exhibit smaller bankfull dimensions than other similar streams; conversely, East Little Llagas Creek (Reach 14) is not presently regulated. It might be noted that the three largest watersheds used for the Inland South Bay and Monterey Bay regional curve are all regulated, likely affecting the slope of that curve. It is probable that the use of present-day channel geometry data introduces bias to the curves as depicted (Figures 6-8, Equations 1-3).

4.5.4 Regionalization

The most useful bankfull geometry values for the design of Upper Llagas Creek Reaches will come from the set of inland streams, principally those draining into the Santa Clara Basin and Pajaro watershed, with the addition of several gages from stations in the Monterey Bay Area located on the eastern slopes of the coastal range (Tables 1 and 2). It is likely that storm and soil types, vegetation patterns, and a history of agricultural land use all contribute to the moderate but distinct regional differences relative to the established and widely used Bay Area curves (Dunne and Leopold, 1978; Riley, 2003).

4.5.5 Geology and soils

Underlying geology, soil type and condition play a large role in natural channel geometry. This aspect of the physical environment was discussed in Chapter 1.2 in this report.

4.5.6 Changes with time and conditions

Bankfull relations need to be applied loosely, with due deference for the changes that come with time in an evolving landscape. Llagas Creek has been incising, likely adjusting to agricultural drainage and land-use changes, for over 100 years, and is likely still adjusting to the 1955 construction of Chesbro Dam (see Figure 4). Similarly, channels do adjust naturally with episodic events (such as fire or floods). The changes proposed in peak flows associated with construction of this Project may be expected to be absorbed gradually by the channel, over periods of many decades; stable channel design must recognize both the initial changes and the more mature adjustments which will occur as the channel receives sediment from upstream and begins to re-vegetate over the decades. There is no absolute 'correct value' for computing an appropriate set of bankfull dimensions, nor should there be. The design objective should be to initially place the stream within an acceptably narrow range of geometries to foster adjustment with time and with sequence of flows that it will experience.

5. APPLICATION

In this chapter, bankfull geometries are used to develop criteria for project Reaches and the proposed confluence of Reaches 5 and 14.

The Project design objective for Reaches 7 and 8 is to provide flood protection for the 1% exceedance probability flood event. The design objective for Reach 14 is to provide flood protection for the 10% exceedance probability flood event. The design objective for Reaches 4, 5, and 6 is to not induce flooding due to upstream Project work (USACE 2011).

The channel geometry values calculated in Tables 6a-6b foster discussion of a concept channel which is dynamic in shape, rather than static. Using the approach of weighing numerous factors (climate, urbanization, regulation, Project goals) will help to guide the development of mitigation features (e.g. channel geometries, plantings) that have some characteristics of a natural system, and as such may help maximize the potential for geomorphic equilibrium and ecological diversity. By building in diversity of planform dimension, we hope to provide an enhanced opportunity for project success, particularly as construction constraints reveal themselves mid-project.

5.1 Project Reaches

Some of the data that was used by USACE (2010) to develop early channel geometry recommendations is provided in Table 5. Reach-by-reach recommendations developed using the non-urbanized bankfull geometry relations of Equations 1, 2, and 3 are provided in Tables 6a and 6b.

Cross-sectional areas for each reach differ from the product of width and depth (Tables 6a-6b). This disparity arises because separate relations were developed for bankfull cross-sectional area, bankfull width, and bankfull depth. The cross-sectional area is considered to be more robust than either width or depth, as the depth equation was manipulated using professional judgment, which introduces an additional level of bias and error. The width equation is more robust than depth, having received no adjustment, but represents just one of two parameters present in the cross-sectional area equation. Therefore, cross-sectional area should be the overall goal of a Reaches' channel geometry, with widths and depths varying to achieve best modeling results.

Recommendations of channel cross-sectional area geometries may change—even after such considerations as rainfall, regulation, geology and soils, and flood protection have been taken into account within the context of available geomorphological science—through the iterative process of running the hydraulic and sediment transport models, as the Project seeks to achieve a stable geomorphic channel configuration while staying within the constraints of the project.

5.1.1 Bankfull geometry channel design approach

The bankfull-geometry channel design approach for this Project is:

1. Develop bankfull geometries as detailed in this report, to test against and to provide the SAM modeling effort with empirical geometries using field-based observations.

2. Use SAM to develop stable low flow channel designs based on revised flow duration curves and effective discharges for each subreach.
3. Develop longitudinally- and cross sectionally-stable overall channel design using sediment yield and budget analysis capabilities in SAM.
4. Synthesize information from bankfull geometrics, sediment rating curves, SAM simulations, soils data, and other Balance field observations, as well as geologic information and (possibly) historical photo analysis to assemble channel design parameters at 30 to 50 cross-sections in the Project Reaches.
5. RMC will incorporate Balance design recommendations, elements, and representative cross sections at 30 to 50 select locations within the Project envelop to develop overall channel design throughout the Project Reaches.
6. Schaaf &Wheeler will simulate hydraulic conveyance through Project Reaches using the design provided by RMC to assess flood routing and conveyance objectives. If conveyance objectives are met, design process will return to RMC and Balance for site specific adjustments and refinements for 30% submittals. If conveyance objectives are not met, design process will return to RMC and Balance for recommended adjustments to meet both geomorphic and hydraulic design criteria.
7. RMC, Balance, and Schaaf & Wheeler will work collaboratively throughout the remainder of initial design process to provide 30% plans for channel dimensions and design that meet geomorphic, hydraulic, and maintenance needs per SCVWD criteria and needs.

5.1.2 Bankfull geometries, with consideration for soils type

The width to depth ratio should vary *generally* with the soil type, specifically the cohesive vs. non-cohesive characteristics of the soil. When soils have high clay content, the banks are more cohesive and channels tend to be relatively more narrow and deep in comparison to non-cohesive bank materials (c.f., Schumm, 1960 and 1963).[3]

The Project should use a width to depth ratio between 4:1 and 6:1 in cohesive soils (Schumm, 1963), while a wider 12:1 to 15:1 ratio is appropriate for the non-cohesive soils (Schumm, 1960). Note that short reaches of contrasting soils can be ignored, but larger trends in soil characteristics should not be. These considerations will lead to better overall design plans, which should result in less maintenance in the long term.

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[3] Perhaps related to the Pleistocene lake history, short sections of cohesive or semi-cohesive banks are mapped as occurring along Llagas Creek, and should be considered in the plans.

The additional coefficients in the width and depth equations in Table 6b bring those values into the correct ratio range by a simple division in the case of widths and multiplication in the case of depths. It is possible that further changes to widths and depths might be necessary based on hydraulic modeling results, but the goal is to utilize the cross-sectional area values as the critical parameter, modified by bank cohesion as a secondary parameter.

Figures 10a-10b and Table 7 are based on USDA Soil Survey Geographic Database (SSURGO, 2011) soils data for Llagas Creek watershed. These data have not been field verified. The maps depict known soil types within approximately 300 feet of the bank on each side in Reaches 4, 5, 6, 7, 8, and 14. These maps indicate where cohesive soils may be present. Soils in upper Reach 7 and all of Reach 8 are dominated by those with clayey characteristics where clay content is above 25% and the plasticity index is greater than 20. Another important consideration is the amount of coverage of a soil, such that when a clayey soil predominates, these soils will be fairly uniformly cohesive.

Please keep in mind three additional and very real caveats regarding soils mapping:

- When the Cardno Entrix soils report (currently in development) is finalized, it may modify or supersede Figures 10a-10b.
- The USDA soils mapping is for surficial soils only, as befits its primary intended use as a guide to cultivation and soil-conservation practices. Llagas Creek has incised throughout most Reaches, such that its lower banks may now be developed in older soils, which may be different than those at the surface. It is the soils of the lower banks which are of particular importance in choosing a width-to-depth ratio. The Soil/ Groundwater characterization report for Reaches 4, 5, and 6 (Peters, 2003) and the forthcoming Cardno Entrix report will provide information on the deeper soils, including a seemingly-indurated 'fanglomerate' in portions of reach 4.
- Dense arboreal vegetation can hold banks in place, acting much as cohesive soils. The maps do not consider the presence of eucalyptus or other linearly-continuous riparian vegetation with interpenetrating roots.

Additionally, Peters and others (2003) note, that a significant proportion of the banks in Reach have been fixed in place by concrete or concrete rubble, and mapped their locations.

5.2 Confluence Reach

Of special note is the confluence of Reaches 5 and 14, which flow together into the upper end of Reach 4. Remnant meander loops or oxbow lakes are detectable from aerial and satellite images to the west-northwest of Reach 5 just before the confluence with Reach 14. The Project design will create a new confluence that includes an increase in channel length and meander amplitude, and provides an opportunity to introduce channel complexity into a managed channel network. The new channel will provide additional accommodation space and temporary storage for water and sediment as it moves through the watershed by allowing flood flows to spread laterally. The lateral flow over a wide bench will promote deposition of fine materials which will in turn strengthen banks over the long term. The Project design concept recognizes that the channel will tend to evolve over time.

In Table 8, Reach 5 non-urbanized bankfull geometry dimensions were calculated for an EXAMPLE meander length, meander amplitude, and radius of curvature to help develop context for the new channel. Figure 11 sets these calculations into a visual context by providing a perspective with respect to remnant channel features in the landscape. The values in Table 8 are reasonable approximations of the meanders represented in Figure 11. The final meander length, meander amplitude, and radius of curvature geometries will depend on additional factors, particularly shape and parcel size of available land. In Figure 3, meander amplitude, meander length, and radius of curvature are shown visually; these values are straightforward to measure.

5.3 Floodplain Benches

Consistent with geomorphic character and variation of streams experiencing dynamic equilibrium, although not quantified by hydraulic geometry, is that benches can be constructed with a slight slope away from the channel side of the bench. This slope may serve some tree species by providing a shorter downward distance to the water table, while also providing an area for over-bank sediment deposition to happen in a fairly naturalized way. The landward slope of interior benches could emulate the natural levees which have developed in several locations in the upper Llagas watershed.

6. DISCUSSION

6.1 Incorporating Channel Geometry in Alignment of the Confluence

Calculations of bankfull geometry, as useful as they may be, should not be considered definitive channel dimensions. They can and should be used as guidance to begin hydraulic and sediment transport modeling. Therefore, the results of calculations presented in this report are guidelines which should help fit the channel alignment and grade to conditions at the site. They are not intended as strict design parameters, and should be adjusted as suggested by hydraulic modeling results. We also note that channel geometries at and immediately upstream of confluences can – and often should be – adapted, recognizing that deposition and depth regimes are typically altered by the mutual backwatering which occurs at major confluences.

The design of the new Reach 5 meander and subsequent confluence with Reach 14 can be adjusted to include adjoining wetlands or floodplains, where the channel can accumulate sediments or woody debris during major floods, then deplete them over the years in an overbank setting, mixed with vegetation as prescribed by others. This should entail a variety of lower bank elevations within the area set aside for this purpose. A more detailed design of this oxbow area is outside the scope of this report.

6.2 Accommodating Ongoing Channel Incision in Channel Geometry Calculations

A long-term concern that should be considered as flood protection designs are implemented is that the Llagas Creek watershed is actively incising at a rate of very roughly 0.4 to 0.8 feet per decade, including the downstream valley-floor channels that include Reaches 5 and 14. This incision will continue to widen the channel. It is recommended that geomorphological theory and practice be incorporated into the design to help minimize the incision rate and anticipate potential problem areas.

7. CONCLUSIONS AND RECOMMENDATIONS

A. Local hydraulic geometry, commonly known as bankfull relationships, is a well-established and well-respected concept appropriate for use in a semi-naturalized flood protection program. It can guide (a) channel cross-sectional geometry, (b) major bedform geometries such as the depth and spacing of pools, or the geometry of bars, and (c) amplitude form and meander curvature.

B. The new Inland South Bay and Monterey Bay curves, one each for cross-sectional area, width, and depth, represent channel geometry data from selected stations in the Santa Clara Valley and along the inland side of the Coast Range in Monterey County. These curves include data gathered by Balance staff and a local data set developed in-house by SCVWD staff. The curves generally conform with earlier regional curves for areas with no development and 30-inch mean annual rainfall previously published by Dunne and Leopold (1978) and the East Bay 25-inch to 30-inch mean annual rainfall of Riley (1999, 2003). The new curves have smaller widths, depths, and cross-sectional areas than these, largely due to lower rainfall, regulation, and regional effects.

C. Direct application of hydraulic geometry appears feasible for Llagas Creek. There are few, if any, bedrock or hardpan controls in the channel, and soils are reasonably uniform within a reach.

D. Using Tables 6a-6b as a template will provide bankfull widths, depths, cross-sectional areas for initial conditions for hydraulic and sediment transport modeling. Modeling results should be used to inform any bankfull geometry changes deemed necessary for the Project design.

E. Bankfull geometries also suggest that floodplain benches, where used, be constructed at heights that conform to the selected bankfull depth. Ongoing incision or other factors may ultimately reduce the elevation of bankfull flow.

8. LIMITATIONS

This report was prepared in general accordance with the accepted standard of practice existing in Northern California at the time the work was performed. No other warranties, expressed or implied, are made. It should be recognized that interpretation and evaluation of flow, subsurface conditions, groundwater, and other physical factors affecting habitat is a difficult and inexact art. Judgment leading to conclusions and recommendations are generally made with an incomplete knowledge of the conditions present. More extensive studies, including additional hydrologic and engineering investigations can reduce the inherent uncertainties associated with such studies. Work has been based on curves previously published by reputable scientists, locally adjusted.

Application of the bankfull relationships to channel design should be conducted under the guidance of a multidisciplinary team of specialists, subject to design by a state-licensed professional. If the client wishes to reduce the uncertainty beyond the level associated with this study, Balance should be notified for additional consultation. In particular, we suggest field calibration using measurements from Llagas Creek and its tributaries if additional work is deemed warranted.

Balance Hydrologics has prepared this report for the client's exclusive use on this particular project. The report is based in part on work performed by Balance and other experts in fluvial geomorphology, information provided by the client, and/ or upon reference values commonly used in the area or developed by sources generally held to be reliable. We may revise the findings and recommendations described in this report as agreed upon following review and comments by the client.

Readers with additional observations or information regarding Llagas Creek or other channel geometries are asked to advise any one of the authors, who will seek to incorporate this information, where warranted.

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TABLES

Table 1. South San Francisco Bay and Monterey Bay Region bankfull geometry, Balance Hydrologics

					Bankfull geometry				Channel		
	Watershed	Station	Drainage Area[1]	Mean Annual Rainfall[2]	Width	Depth	Area	Discharge	Slope	Roughness	Reference
			(square miles)	(inches)	(feet)	feet)	(square feet)	(cubic feet per second)			
Inland	Llagas Creek	Reach 5	(29.3)	24	25.7	4.9	126				Hecht field notes, 2011
		Buena Vista	(61.7)	24	29.5	5.1	152				Owens and Baggett, 2011
	East Little Llagas Creek	Reach 14	24.1	18	51.5	2.7	113.4				Hecht field notes, 2011
	San Francisquito	Stanford pump station	(37.4)	26.0	38.0	2.5	80.0	...	...	...	Richmond field notes, 2011
	Stevens Creek	Blackberry Farm	(21)	27.0	25.0	2.0	50.0	...	0.012	...	Balance and SCVWD field notes (2005)
	Upper Penitencia Creek	Berryessa Station	(24)	18.0	24.0	2.0	48.0	...	0.010	...	Chartrand and others (2011)
	Upper Carmel River	Bluff Camp	48.0	37.0	54.8	3.4	188.0	1290	...	0.052	Hecht, 1981
		Miller Fork	15.0	37.0	34.0	2.1	71.3	401	0.032	0.072	Hecht, 1981
		Carmel Camp	31.8	37.0	37.0	2.5	90.4	565	0.026	0.065	Hecht, 1981
Coastal	Gazos Creek	Site Q	11.3	34.0	41.0	5.8	118.9	...	...	...	Chartrand field notes (2000)
	Hare Creek	Upstream of Hare #1 Reservoir	1.0	57.0	8.0	3.2	25.6	110	0.012	0.048	Hecht field notes (1977)
	Waddell Creek	West Fork	9.4	42.0	31.5	2.0	61.0	333	0.010	0.043	Hecht field notes (1978)
		East Fork	12.4	46.0	30.0	3.0	90.6	401	0.007	0.580	Hecht field notes (1978)
		At Shapavolv weir	23.5	43.0	56.0	2.7	150.0	694	0.003	0.037	Hecht field notes (1978)
	Zayante Creek	Waner Way	11.0	48.0	26.0	4.8	95.0	680	0.016	0.052	Hecht field notes (1977)
	Wilder Creek	Seven Name	0.6	31.0	12.7	1.3	17.0	49	0.013	0.065	Hecht, 1999
		W-1	0.9	31.0	0.9	0.9	18.6	59	0.013	0.049	Hecht, 1999
		W-2	1.2	31.0	0.8	0.8	13.0	42	0.015	0.047	Hecht, 1999
	Soquel Creek	East Fork at Camp Lorna (XS 2)	1.6	40.0	14.4	0.6	4.4	...	...	...	Strudley and others, 2009
		East Fork at Camp Lorna (XS 4)	1.6	40.0	22.5	3.1	34.9	...	...	...	Strudley and others, 2009
		Main stem USGS gage 11160000	40	34	51	5.2	265.2	...	...	...	Strudley and others, 2009
	Corralitos Creek	Browns Valley	6.1	26.0	25.5	1.8	45.9	...	...	...	Strudley and others, 2009, 2010, 2011; Hecht and Woyshner, 1984
		Old Logging Road	7.4	26.0	30.0	2.9	69.6	...	...	...	Strudley and others, 2009, 2010, 2011
		Rider Road (XS 7)	9.7	26.0	35.0	1.3	27.7	...	...	...	Strudley and others, 2009, 2010, 2011; Hecht and Woyshner, 1984
		Jensen's Cold Storage	21.5	26.0	42.0	3.3	91.8	...	...	...	Strudley and others, 2009, 2010, 2011
	Little Sur River	S. Fork Green Bridge	11.3	40.0	25.0	2.7	60.0	...	0.010	0.042	Strudley field notes, 2008
		N. Fork Green Bridge	23.0	40.0	46.0	3.0	138.0	...	...	...	Strudley field notes, 2008

Notes

1. Drainage Area	Above key section; values in parentheses are regulated.
2. Rainfall	Estimated mean annual precipitation in watershed upstream from key section (Rantz, 1971 or select publications for southernmost stations)

Table 2. South San Francisco Bay and Monterey Bay Region bankfull geometry, others' data

					Bankfull geometry				Channel		
	Watershed	Station	Drainage Area[1]	Mean Annual Rainfall[2]	Width	Depth	Area	Discharge	Slope	Roughness	Reference
			(square miles)	*(inches)*	*(feet)*	*feet)*	*(square feet)*	*(cubic feet per second)*			
Inland	Calabazas Creek	upstream of Regnart Creek	7.6	22	...	...	57	190	...	...	Xu and others, 2009
											Xu and others, 2009
	Adobe Creek	upstream of West Edith Rd	7	20	...	...	54	280	...	...	Xu and others, 2009
											Xu and others, 2009
	Guadalupe River	at Reach 6	(67)	18	...	...	226	800	...	...	Xu and others, 2009
		at St Johns	(88)	18	...	...	200	900	...	...	Xu and others, 2009
		Almaden Gage 23B	(45)	24	...	...	240	750	...	...	Xu and others, 2009
		downstream of Hwy 101	(98)	16	...	...	320	1000	...	...	Xu and others, 2009
Coastal	Soquel	East Branch at Soquel Demonstration Forest	10.9	40	49.6	1.5	74.1	395.6	...	...	Howell, 2009
		at Soquel	40.2	36	54.3	6.5	368.4	1827.5	...	...	Howell, 2009
	San Vicente	at CEMEX near Davenport	10.5	44	25.4	2.2	55.7	491.6	...	...	Howell, 2009
	Opal	at Big Basin Redwoods State Park	3.4	40	27.1	0.6	14.9	47.5	...	...	Howell, 2009
	Fall	at Felton	5.0	46	19.1	1.6	30.8	212.2	...	...	Howell, 2009
	San Lorenzo River	at Big Trees	106	48	104.2	9.6	987.7	5136.6	...	...	Howell, 2009
		near Boulder Creek	6.2	54	23.9	1.7	108.4	383.8	...	...	Howell, 2009
	Pescadero	near Pescadero	45.9	38	52.5	5.9	312.1	1352.2	...	...	Howell, 2009
Greater Bay Area	Bay Area	published curve for 30" rainfall	0.1	30	7	0.8	5.5	...	...	...	Dunne and Leopold, 1978
			100	30	80	5	450	...	...	...	Dunne and Leopold, 1978
	East Bay	published curve	0.1	25	...	...	4.9	...	...	...	Riley, 2003
			100	25	...	...	500	...	...	...	Riley, 2003

Notes

1. Drainage Area	Above key section; values in parantheses have more than 10% of regulated watershed area
2. Rainfall	Estimated mean annual precipitation in watershed upstream from key section (Rantz, 1971 or Sa'ah and Naan, 1989)

Table 3. Design Parameters

	Bankfull Cross-sectional Area[1] (square feet)	Normative Bankfull Width[1] (feet)	Normative Bankfull Depth[1] (feet)	USGS 2-year peak (Rantz, 1971) (cubic feet per second)	Amplitude[2] (feet)	Meander Length[3] (feet)	Radius of Curvature[4] (feet)
San Francisco Bay Region (Dunne and Leopold, 1978)	$XS_a = 24 * DA^{0.64}$	$W = 16 * DA^{0.35}$	$D = 1.5 * DA^{0.27}$	$Q = 53 * DA^{0.93}$	$A = 2.7 * W^{1.1}$	$L = 10.9 * W^{1.01}$	$r = (L/4.7)^{(1/0.98)}$
San Francisco East Bay Region (Riley, 2003)	$XS_a = 18 * DA^{0.63}$	...	...	...	$A = 2.7 * W^{1.0}$	...	
San Francisco Bay Region, Inland South Bay and Monterey Bay relations (Balance, 2011[5])	$XS_a = 10.95 * DA^{0.68}$	$W = 11.80 * DA^{0.31}$	$D = 0.98 * DA^{0.28}$	...	...	...	
USGS San Francisco Bay Region flood-frequency analysis (Rantz, 1971)[6,7,8]		...	...	$Q_{p2} = 0.069A^{0.913}P^{1.965}$	...	...	...

Notes

1. Publications provided plots, rather than equations. We developed equations, limited to 2 significant figures, to fit these plots. DA represents drainage area at station.
2. Amplitude is defined as the maximum cross-valley distance between successive meanders, e.g., the distance between the "crest" and "trough" of a sinusoidal curve. Equation from Leopold and Wolman (1960); A = amplitude; see Figure 3 for visual conte
3. Meander length is defined as the down-valley distance from one crest to another, or one trough to another, of a meandering channel. Equation from Leopold and Wolman (1960); L = meander length; see Figure 3 for visual context
4. Radius of curvature is defined as the radius of an approximating circle (see Figure 10 for visual context). Equation from Leopold and Wolman (1960); r = radius, L = meander length
5. Balance, 2011 regression equations are based on inland stations from Table 1 and Table 2, and depicted in Figures 6, 7, and 8.
6. In subsequent tables, area (A, DA) changes within respect to drainage areas provided by USACE (2010)
7. Precipitation (P) in Llagas watershed averages 18-24 inches per year. The highest average value of 24 inches was used in subsequent discharge calculations
8. Subsequently referred to as USGS 2-year peak in non-urbanized areas of the Bay Area

Table 4. Balance Hydrologics geomorphological bankfull discharge context for Upper Llagas Creek Flood Control Project in urbanized and non-urbanized reaches, Santa Clara County, California

Project Reach	Sub-reach	Rantz 2-year peak in non-urbanized areas of the Bay Area[1]	Rantz 2-year peak in 60% urbanized, 60% channelized areas of the Bay Area[2,3,4]	USACE 50% exceedance flows[5]	Drainage area at downstream extent of each sub-reach[5]
		(cubic feet per second)	*2.25 coefficient*		*(square miles)*
Reach 8	**R8S4**	52	118	186	1.5
	R8S3	67	150	270	2.0
	R8S2	78	175	315	2.4
	R8S1	85	192	344	2.6
Reach 7	**R7S4**	85	192	344	2.6
	R7S3	108	243	454	3.4
	R7S2	129	290	542	4.1
	R7S1	175	394	673	5.7
Reach 6	**R6S2**	733	–	929	27.5
	R6S1	871	–	1101	33.2
Reach 5	**R5**	925	–	1101	35.5
Reach 4	**R4**	1533	–	2840	61.7
Reach 14	**R14S1**	113	254	929	6.6
	R14S2	233	524	1187	14.5
	R14S3	297	667	1419	19.0
	R14S4	325	732	1490	21.0

Notes

1. Results based on Rantz (1971) equation using an assumption of non-urbanized areas in the lower reaches 4, 5, 6 and 14
2. Results based on Rantz (1971) ratios of 2-year flood-peak magnitude
3. Reaches 7, 8, and 14 were assumed to be 60% channelized and 60% urbanized; the coefficient may change if these assumptions change
4. Reaches 4, 5, 6 have double dashes to indicate that the urbanization/channelization effects are not applicable in these dominately rural watersheds
5. USACE 2010 data

Table 5. Selected USACE data for Upper Llagas Creek Flood Control Project, Santa Clara County, California[1]

Project Reach	Reach Description	Sub reach	Sub reach length (feet)	Drainage area at downstream extent (square miles)	USACE proposed gradient %	USACE proposed bench width (feet)
Reach 8	West Little Llagas Creek, downtown Morgan Hill	**R8S4**	1,070	1.53	0.26%	0
		R8S3	2,330	1.99	0.22%	0
		R8S2	2,400	2.35	0.26%	0
		R8S1	460	2.61	0.21%	0
Reach 7	Dunne Ave to Llagas Creek	**R7S4**	1,140	2.61	0.26%	0
		R7S3	3,900	3.37	0.24%	variable
		R7S2	2,200	4.09	0.23%	variable
		R7S1	6,400	5.73	0.23%	0
Reach 6	diversion channel to 700 feet upstream Hwy 101	**R6S2**	2,900	27.51	0.36%	-
		R6S1	16,400	33.24	0.31%	variable
Reach 5	700 feet upstream Hwy 101 to East Little Llagas Creek	**R5**	2,100	35.5	0.31%	variable
Reach 4	Llagas Creek to Panther Creek	**R4**	12,370	61.7	0.20%	10
Reach 14	East Little Llagas Creek confluence with Llagas Creek to 2400 feet upstream of San Martin Ave	**R14S1**	5,800	6.58	0.29%	0
		R14S2	7,200	14.54	0.37%	0
		R14S3	4,400	18.96	0.36%	0
		R14S4	500	20.97	0.33%	0

Notes

1. All data from USACE 2010

Table 6a. Balance Hydrologics bankfull geometry calculations for non-cohesive soils in Llagas Creek: Reaches 4, 5, 6, two subreaches of Reach 7, and Reach 14, Santa Clara County, California[1,2,3]

Project Reach	Sub-reach	Bankfull cross-sectional area	Bankfull Width for non-cohesive soils	Bankfull Depth for non-cohesive soils	Computed width to depth ratio for non-cohesive soils	Empirical width to depth ratio range for non-cohesive soils[1]
		$XS_a = 10.95*DA^{0.68}$	$W = 11.80*DA^{0.31}$	$D = 0.98*DA^{0.28}$	should calculate to approximately 12:1-15:1	12:1 - 15:1
		(square feet)	*(feet)*	*(feet)*	*non-dimensional*	*non-dimensional*
Reach 7	**R7S2**	28.5	18.3	1.5	12.6	12:1 - 15:1
	R7S1	86.7	20.3	1.6	12.7	12:1 - 15:1
Reach 6	**R6S2**	104.3	33.0	2.5	13.3	12:1 - 15:1
	R6S1	118.6	35.0	2.6	13.4	12:1 - 15:1
Reach 5	**R5**	124.0	35.7	2.7	13.4	12:1 - 15:1
Reach 4	**R4**	180.6	42.4	3.1	13.6	12:1 - 15:1
Reach 14	**R14S1**	39.4	21.2	1.7	12.7	12:1 - 15:1
	R14S2	67.6	27.1	2.1	13.0	12:1 - 15:1
	R14S3	81.0	29.4	2.2	13.2	12:1 - 15:1
	R14S4	86.7	30.3	2.3	13.2	12:1 - 15:1

Notes

1. A typical width:depth ratio range for channels in non-cohesive soils is 12:1-15:1 (Schumm, 1960)
2. Assumes that soils at lower bank depths are similar to those mapped at surface, which does not necessarily hold in all cases.
3. These geometries may need adjustment for increased discharges based on urbanization effects not accounted for here.

Table 6b. Balance Hydrologics bankfull geometry calculations for cohesive soils in Llagas Creek: two subreaches of Reach 7, and Reach 8, Santa Clara County, California[1,5]

Project Reach	Sub-reach	Bankfull cross-sectional area[2]	Bankfull Width for cohesive soils[3]	Bankfull Depth for cohesive soils[4]	Computed width to depth ratio for cohesive soils	Empirical width to depth ratio range for cohesive soils[1]
		$XS_a = 10.95*DA^{0.68}$	$W = (11.80*DA^{0.31})/1.5$	$D = (0.98*DA^{0.28})*1.5$	should calculate to approximately 4:1-6:1	4:1 - 6:1
		(square feet)	*(feet)*	*(feet)*	*non-dimensional*	*non-dimensional*
Reach 8	**R8S4**	14.6	9.0	1.7	5.4	4:1 - 6:1
	R8S3	17.5	9.7	1.8	5.5	4:1 - 6:1
	R8S2	19.6	10.3	1.9	5.5	4:1 - 6:1
	R8S1	21.0	10.6	1.9	5.5	4:1 - 6:1
Reach 7	**R7S4**	21.0	10.6	1.9	5.5	4:1 - 6:1
	R7S3	25.0	11.5	2.1	5.6	4:1 - 6:1

Notes

1. A typical width:depth ratio range for channels in cohesive soils is 4:1-6:1 (Schumm, 1960)
2. Cross-sectional area does not change, only the W:D ratio changes in cohesive soils
3. A coefficient of 1.5 was used to conform widths to the smaller W:D ratio, where the regression equation is divided by 1.5
4. A coefficient of 1.5 was used to conform depths to the smaller W:D ratio, where the regression equation is multiplied by 1.5
5. These geometries may need adjustment for increased discharges based on urbanization effects not accounted for here.

Table 7. Properties and characteristics of surficial soils that adjoin Upper Llagas Creek, Santa Clara County, California

Soil Symbol	Soil Name[1]	Depth[2] (in)	USDA Texture[3]	Clay[4] (percent)	Liquid Limit[5] (percent)	Plasticity Index[6]	Calcium Carbonate[7] (percent)
ArA:							
	ARBUCKLE	0-20	Gravelly loam	12-25	15-20	5-10	0
		20-40	Gravelly loam	18-27	15-20	5-10	0
		40-60	Very gravelly sandy loam	15-20	15-25	5-10	0
CoB:							
	CORTINA	0-8	Very gravelly loam	10-25	0	NP	0
		8-60	Sr to very gravelly sandy loam to very gravelly loam	5-25	0	NP	0
CrA:							
	CROPLEY	0-14	Clay	40-60	50-60	30-40	0
		14-36	Clay	40-60	50-60	30-40	0
		36-60	Clay	40-60	50-60	30-40	0-1
GaA:							
	GARRETSON	0-19	Loam	15-25	25-35	5-10	0
		19-40	Very fine sandy loam	18-27	25-35	5-10	0
		40-60	Stratified sand	0-5	0	NP	0
GbB:							
	GARRETSON	0-6	Gravelley loam	15-27	25-35	5-10	0
		6-60	Gravelly clay loam, Gravelly loam	18-30	25-35	5-10	0
GoE2:							
	GILROY	0-6	Clay loam	27-30	30-40	10-15	0
		6-21	Clay loam	30-35	30-40	10-15	0
		21-25	Unweathered bedrock	---	---	---	---
GoF:							
	GILROY	0-8	Clay loam	27-30	30-40	10-15	0
		8-21	Clay loam	30-35	30-40	10-15	0
		21-25	Unweathered bedrock	---	---	---	---
HfC:							
	HILLGATE	0-10	Silt loam	10-25	20-35	5-15	0
		10-40	Clay, Clay loam	35-45	35-45	15-25	0
		40-60	Gravelly clay loam	27-35	25-30	10-15	0
KeA:							
	KEEFERS	0-23	Clay loam	27-35	30-35	10-15	0
		23-38	Gravelly clay loam	30-40	30-40	10-20	0
		38-60	Gravelly clay, Very gravelly clay loam	35-60	40-70	20-40	0
KeC2:							
	KEEFERS	0-23	Clay loam	27-35	30-40	10-20	0
		23-38	Gravelly clay loam	30-40	30-40	10-20	0
		38-60	Gravelly clay, Very gravelly clay loam	35-60	40-70	20-40	0
LrC:							
	LOS ROBLES	0-14	Clay loam	27-35	30-40	10-20	0
		14-60	Gravelly clay loam	27-35	30-40	15-20	0
McB:							
	MAXWELL	0-25	Clay	40-55	50-70	25-35	0
		25-46	Clay	40-55	50-70	25-35	0
		46-60	Gravelly clay loam	30-40	30-40	15-25	1-5
PoA:							
	PLEASANTON	0-18	Loam	12-25	25-35	5-10	0
		18-44	Clay loam, Gravelly clay loam	27-35	35-45	15-20	0
		44-66	Gravelly sandy clay loam	20-25	30-35	10-15	0
PpA:							
	PLEASANTON	0-18	Gravelly loam	12-25	25-35	5-10	0
		18-44	Gravelly clay loam	27-35	35-45	15-20	0
		44-66	Gravelly sandy clay loam	20-25	30-35	10-15	0
RaA:							
	RINCON	0-19	Clay loam	27-35	40-50	20-30	0
		19-37	Gravelly clay, Gravelly clay laom	35-45	45-55	20-30	0
		37-50	Clay loam, Gravelly clay loam	27-30	35-40	15-20	0-1
		50-72	Clay loam	27-35	30-40	10-20	0-1
RaC2:							
	RINCON	0-19	Clay loam	27-35	30-40	20-30	0
		19-37	Gravelly clay, Gravelly clay loam	35-45	40-60	20-30	0
		37-50	Clay loam, Gravelly clay loam	27-30	25-40	15-20	0-1
		50-72	Clay loam	27-35	30-40	10-20	0-1
Rg:							
	RIVERWASH	0-6	Sand	0-1	0	NP	0
		6-60	Sr to coarse sand to sandy loam	0-5	0	NP	0
SdA:							
	SAN YSIDRO	0-20	Loam	15-25	15-25	5-10	0
		20-36	Clay, Clay loam	35-45	45-55	20-30	0
		36-50	Clay loam	27-35	35-50	15-25	0-1
		50-60	Gravelly clay loam, Sandy clay loam	20-30	35-45	15-20	0-1
YaA:							
	YOLO	0-29	Loam	15-27	25	5-15	0
		29-60	Sr to loam to silty clay loam	20-35	30-40	10-20	0-1
YeA:							
	YOLO	0-29	Silty clay loam	27-35	25-35	5-15	0
		29-60	Sr to loam to silty clay loam	20-35	30-40	10-20	0-1
ZaA:							
	ZAMORA	0-15	Loam	15-25	25-35	5	0
		15-35	Clay loam, Silty clay loam	27-35	35-45	15-20	0
		35-55	Sandy clay loam	20-25	30-35	10-15	0
		55-70	Gravelly sandy clay loam	20-25	30-35	10-15	0
ZbA:							
	ZAMORA	0-15	Clay loam	27-30	35-40	15-20	0
		15-35	Clay loam, Silty clay loam	27-35	35-45	15-20	0
		35-58	Sandy clay loam	20-25	30-35	10-15	0
		58-70	Gravelly sandy clay loam	20-25	30-35	10-15	0
ZbC:							
	ZAMORA	0-15	Clay loam	27-30	35-40	15-20	0
		15-35	Clay loam, Silty clay loam	27-35	35-45	15-20	0
		35-58	Sandy clay loam	20-25	30-35	10-15	0
		58-70	Gravelly sandy clay loam	20-25	30-35	10-15	0

Notes

1. Predominate soil series within this group

2. Depth to the upper and lower boundaries of each layer is indicated.

3. Texture is given in the standard terms used by the U.S. Department of Agriculture. These terms are defined according to percentages of sand, silt, and clay in the fraction of the soil that is less than 2 millimeters in diameter. "Loam," for example, is soil that is 7 to 27 percent clay, 28 to 50 percent silt, and less than 52 percent sand. If the content of particlues coarser than sand is 15 percent or more, an appropriate modifier is added, for example, "gravelly."

4. Clay as a soil separate consists of mineral soil particles that are less than 0.002 millimeter in diameter. The estimated clay content of each soil layer is given as a percentage, by weight, of the soil material that is less than 2 millimeters in diameter.

5. The liquid limit is the water content at which a soil changes from plastic to liquid behavior.

6. The plasticity index is a measure of the plasticity of a soil. The plasticity index is the size of the range of water contents where the soil exhibits plastic properties. Soils with a high PI (20+) tend to be clay, those with a lower PI tend to be silt, and a PI of 0 (non-plastic) tend to have little or no silt or clay.

7. Calcium carbonate is the percent of carbonates, by weight, in the fraction of the soil less than 2 millimeters in size. The availability of plant nutrients is influenced by the amount of carbonates in the soil. Incorporating nitrogen fertilizer into calcareous soils helps to prevent nitrite accumulation and ammonium-N volatilization.

Yellow highlight indicates predominately clay soils, where cohesive soil criteria should be used

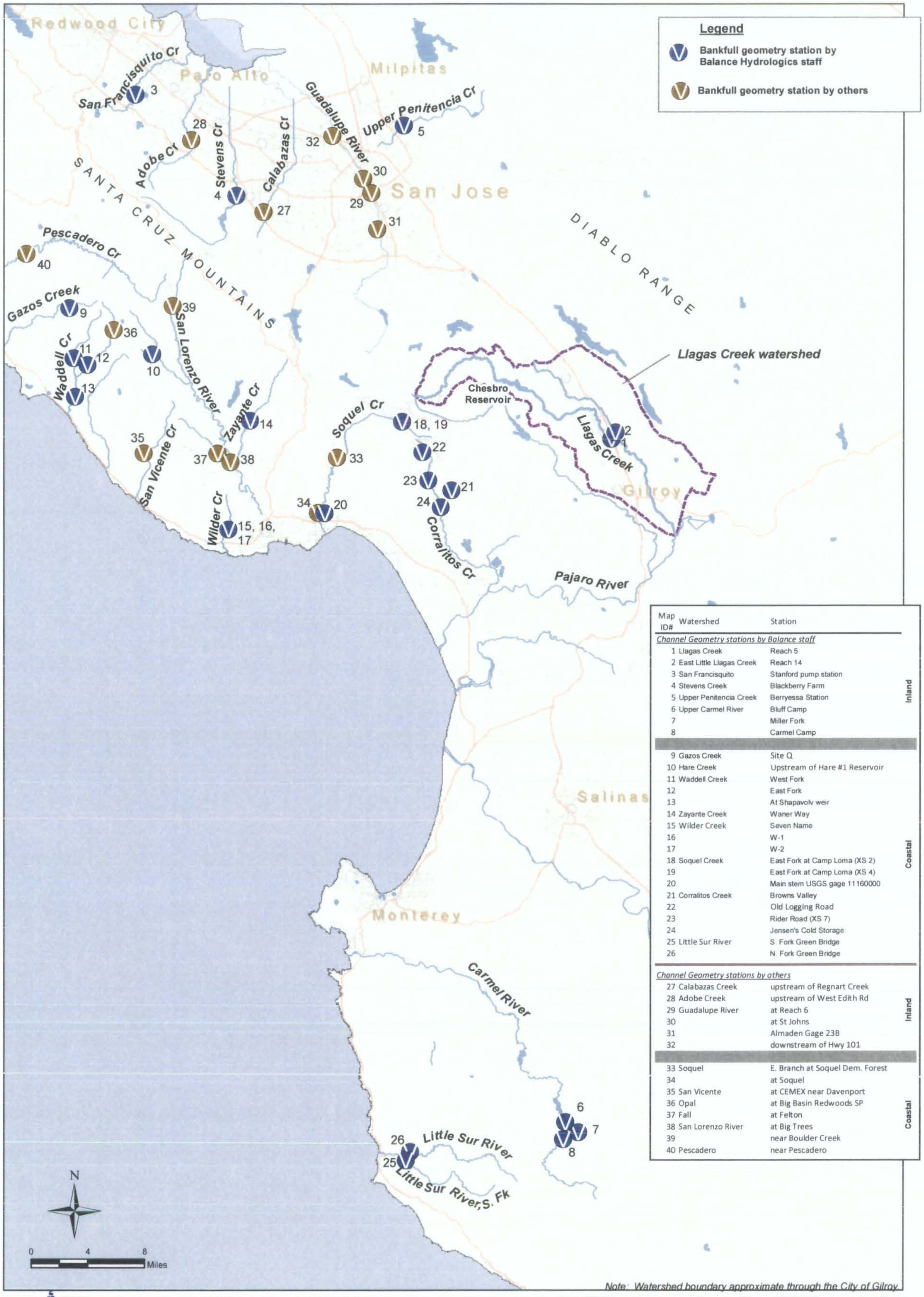
Table 8. Calculations for bankfull channel geometry for proposed meander in Reach 5 at the confluence of Reach 14

	Bankfull Cross-sectional Area	Bankfull Width	Bankfull Depth	Bankfull Discharge	Amplitude[4]	Meander Length[5]	Radius of Curvature[5]
	$XS_a = 10.95*DA^{0.68}$	$W = 11.80*DA^{0.31}$	$D = 0.98*DA^{0.28}$	$Q_{p2} = 0.069A^{0.913}P^{1.965}$	$A = 2.7*W^{1.0}$	$L = 10.9*W^{1.01}$	$r_m = (L/4.7)^{(1/0.98)}$
	(square feet)	*(feet)*	*(feet)*	*(cubic feet per second)*	*(feet)*	*(feet)*	*(feet)*
Reach 5 at confluence with reach 14 [1,2,3]	124	35.7	2.7	925	96	403	94

Notes

1. Drainage area (DA, A) of 35.5 used, as this is the total area at the bottom of reach 5. Reach 14 will join at a confluence, but is not considered here
2. Precipitation averages 18-24 inches per year. To take into consideration highest average runoff events, the 24 inch value for (P) is used here
3. Note that cross-sectional area, width, and depth values are equal to those presented in Tables 6 and 7
4. Amplitude equation from Riley (2003), used because mean annual rainfall is more similar to the South Bay than using the equation from Dunne and Leopold (1978)
5. Meander length and radius of curvature equations from Dunne and Leopold (1978), as Riley (2003) does not provide this equation

FIGURES



Map ID#	Watershed	Station	
Channel Geometry stations by Balance staff			
1	Llagas Creek	Reach 5	Inland
2	East Little Llagas Creek	Reach 14	
3	San Francisquito	Stanford pump station	
4	Stevens Creek	Blackberry Farm	
5	Upper Penitencia Creek	Berryessa Station	
6	Upper Carmel River	Bluff Camp	
7		Miller Fork	
8		Carmel Camp	
9	Gazos Creek	Site Q	Coastal
10	Hare Creek	Upstream of Hare #1 Reservoir	
11	Waddell Creek	West Fork	
12		East Fork	
13		At Shapavolv weir	
14	Zayante Creek	Waner Way	
15	Wilder Creek	Seven Name	
16		W-1	
17		W-2	
18	Soquel Creek	East Fork at Camp Loma (XS 2)	
19		East Fork at Camp Loma (XS 4)	
20		Main stem USGS gage 11160000	
21	Corralitos Creek	Browns Valley	
22		Old Logging Road	
23		Rider Road (XS 7)	
24		Jensen's Cold Storage	
25	Little Sur River	S. Fork Green Bridge	
26		N. Fork Green Bridge	
Channel Geometry stations by others			
27	Calabazas Creek	upstream of Regnart Creek	Inland
28	Adobe Creek	upstream of West Edith Rd	
29	Guadalupe River	at Reach 6	
30		at St Johns	
31		Almaden Gage 23B	
32		downstream of Hwy 101	
33	Soquel	E. Branch at Soquel Dem. Forest	Coastal
34		at Soquel	
35	San Vicente	at CEMEX near Davenport	
36	Opal	at Big Basin Redwoods SP	
37	Fall	at Felton	
38	San Lorenzo River	at Big Trees	
39		near Boulder Creek	
40	Pescadero	near Pescadero	

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Figure 1. Locations of regional bankfull geometry stations used in the analysis for the Llagas Creek watershed, Santa Clara County, California.

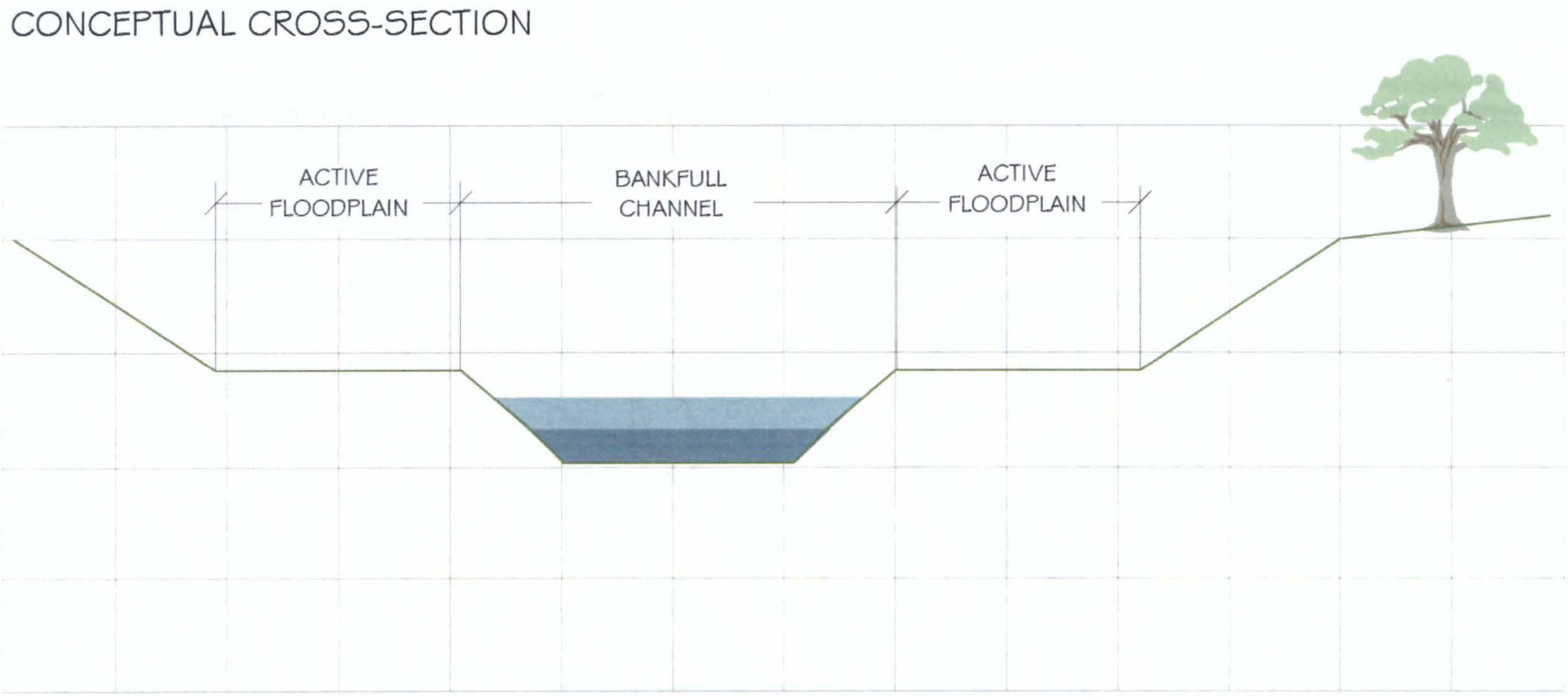

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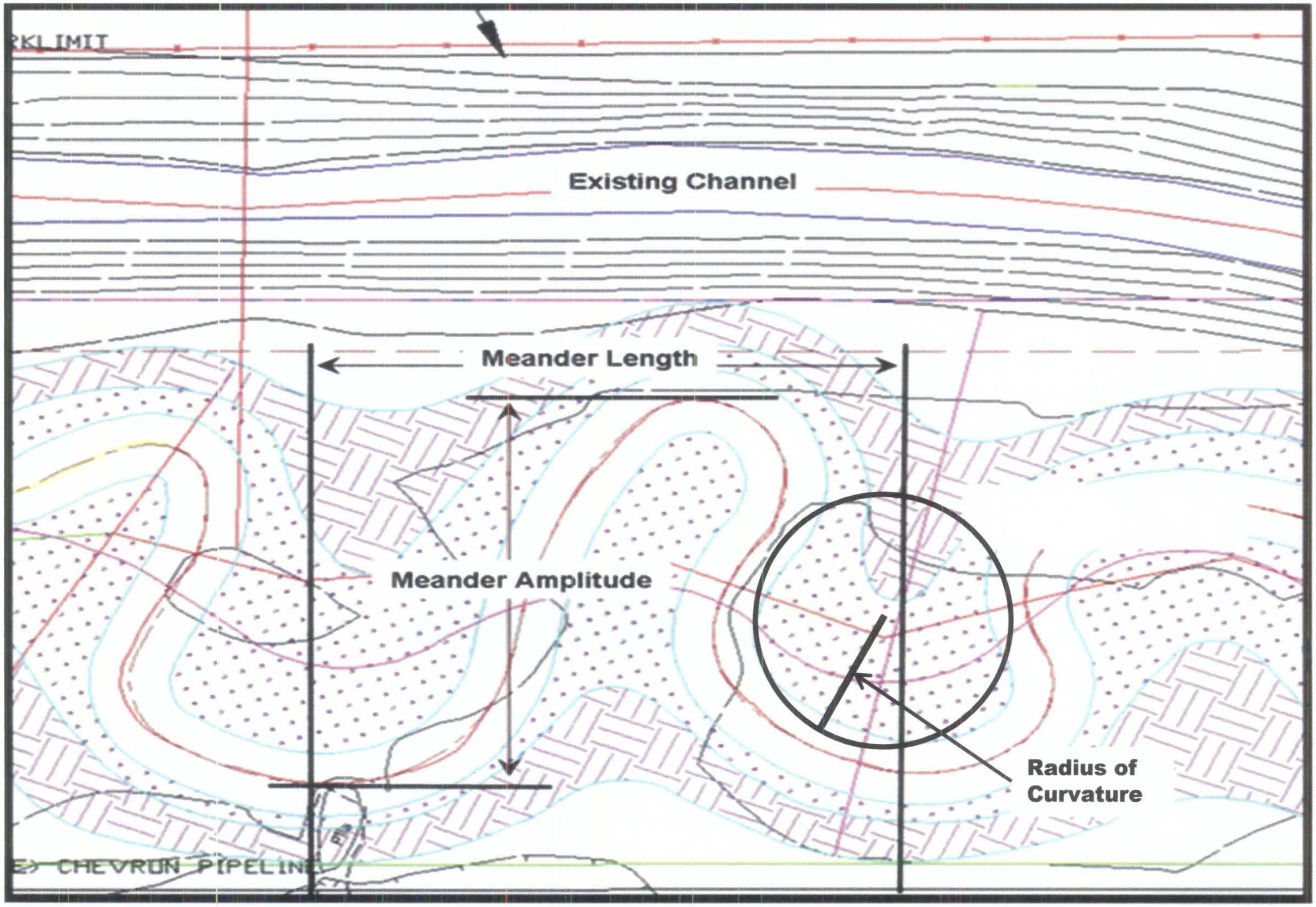
Figure 2. **Conceptual bankfull geometry in a natural channel.** Bankfull cross-sectional area is roughly equivalent to the water surface elevation of a ~1.5 to 2 year flood recurrence interval. Flood flows greater than bankfull would spill onto the adjacent floodplain. Allowing flood flows to move onto a floodplain promotes channel stability by slowing water velocities and allowing sediments to drop out of the water column.



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209164 Conceptual meander geometry

Figure 3. **Meander wavelength, meander amplitude and radius of curvature of a conceptual channel design for a project on Wrigley Creek, Milpitas, California.** Notice the degree of complexity compared to the schematic of an existing straight channel. Source: Chartrand,, 2009.

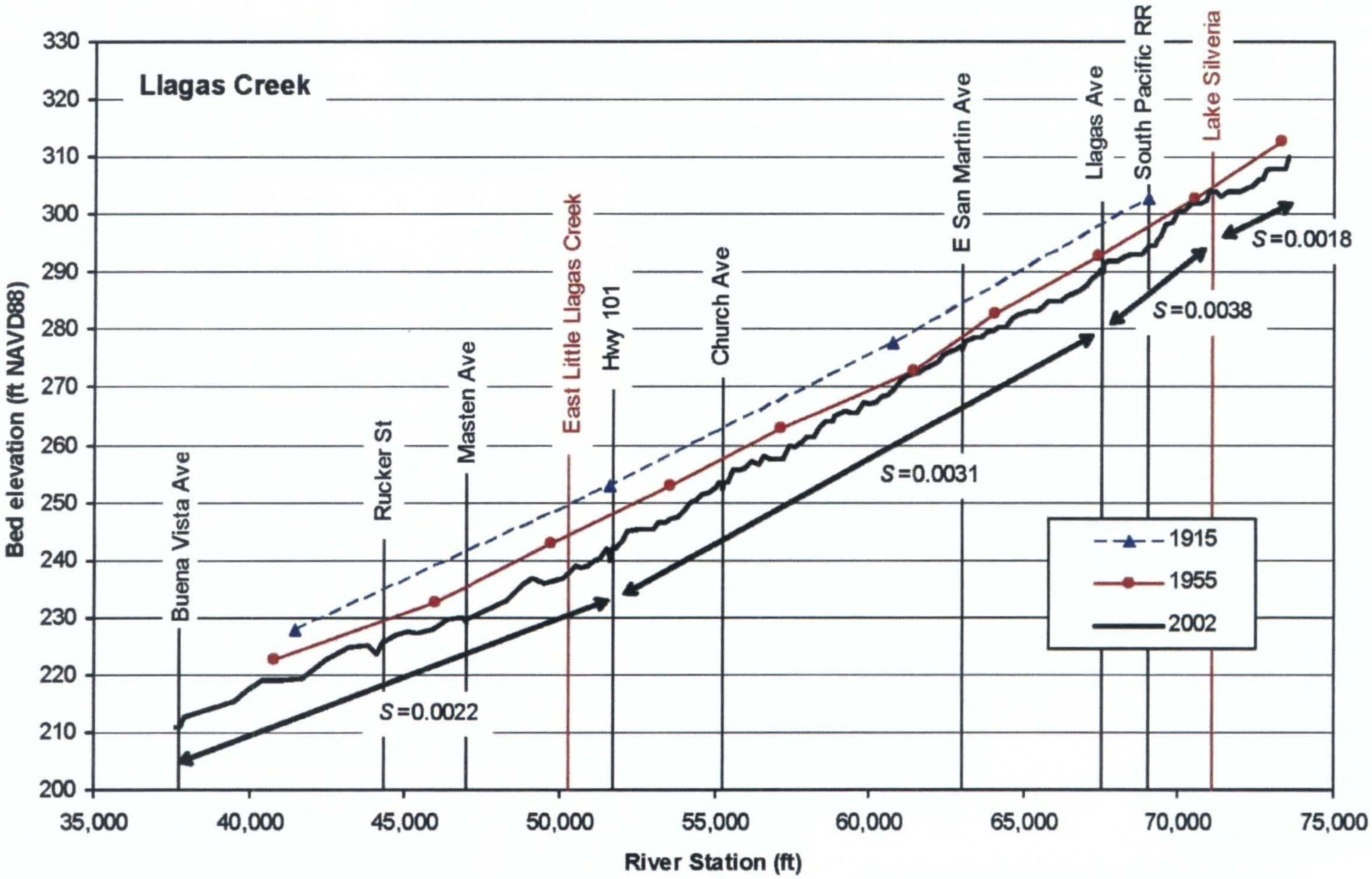

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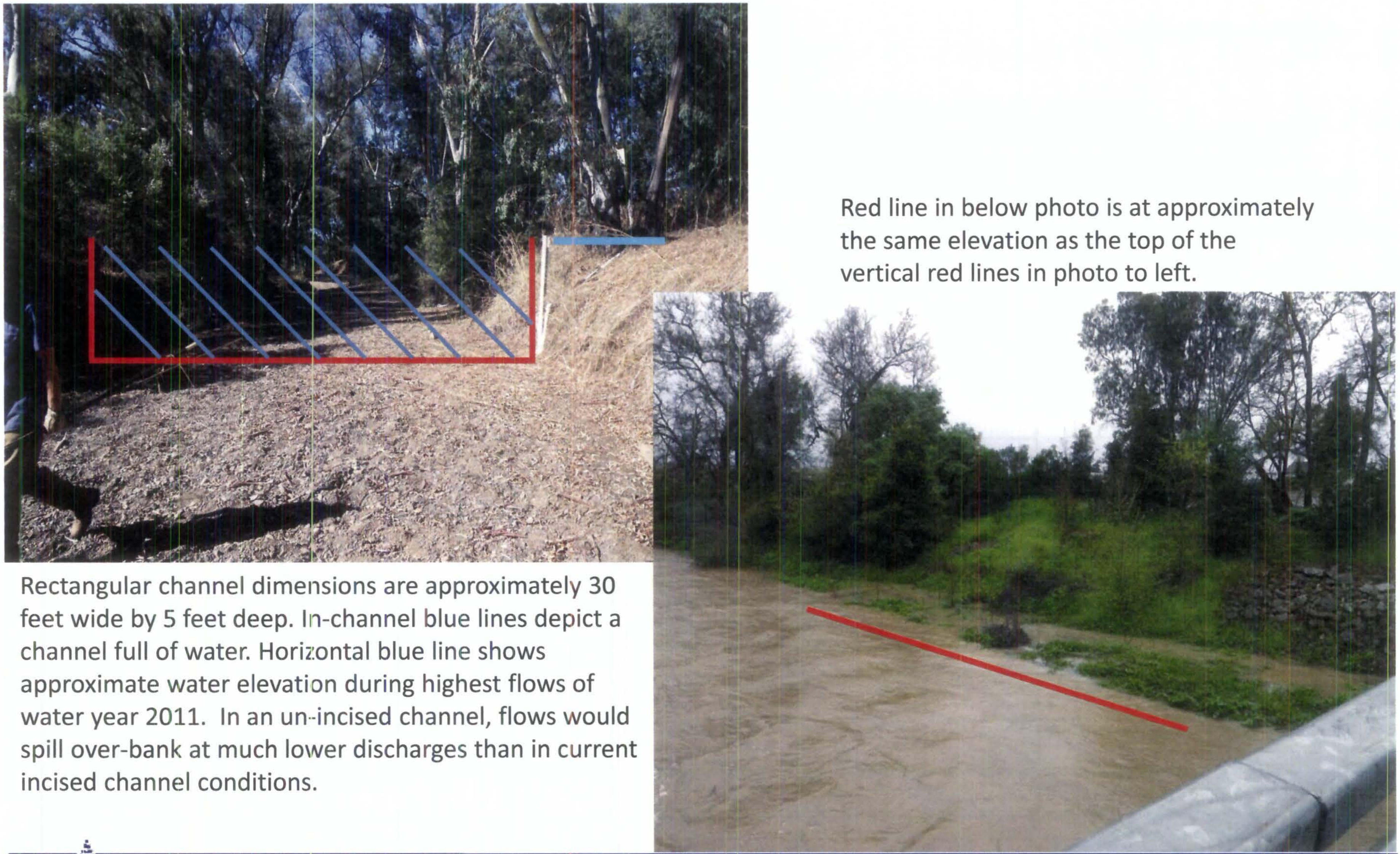
Figure 4. **History of incision 1915-present, Llagas Creek, Santa Clara County, California.** Longitudinal profiles from 1915, 1955, and 2002 show progressive channel incision 12 feet at the confluence of East Little Llagas and Llagas Creeks. Source: Nobel and NWC, 2008.



Red line in below photo is at approximately the same elevation as the top of the vertical red lines in photo to left.

Rectangular channel dimensions are approximately 30 feet wide by 5 feet deep. In-channel blue lines depict a channel full of water. Horizontal blue line shows approximate water elevation during highest flows of water year 2011. In an un-incised channel, flows would spill over-bank at much lower discharges than in current incised channel conditions.

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Figure 5. **Incised Llagas Creek at Buena Vista Avenue, dry and wet conditions, Santa Clara County, California.** Upper left photo looking upstream at the Balance streamflow gage (at white stake) in October 2010 upstream of the bridge. Note the rectangular, incised channel. Lower right photo looking downstream shows a 508 cfs flow on March 24, 2011, with flows beginning to reach an incised 'bankfull' (USGS gage #11153650 recorded highest flow in nine years on March 25, 2011).

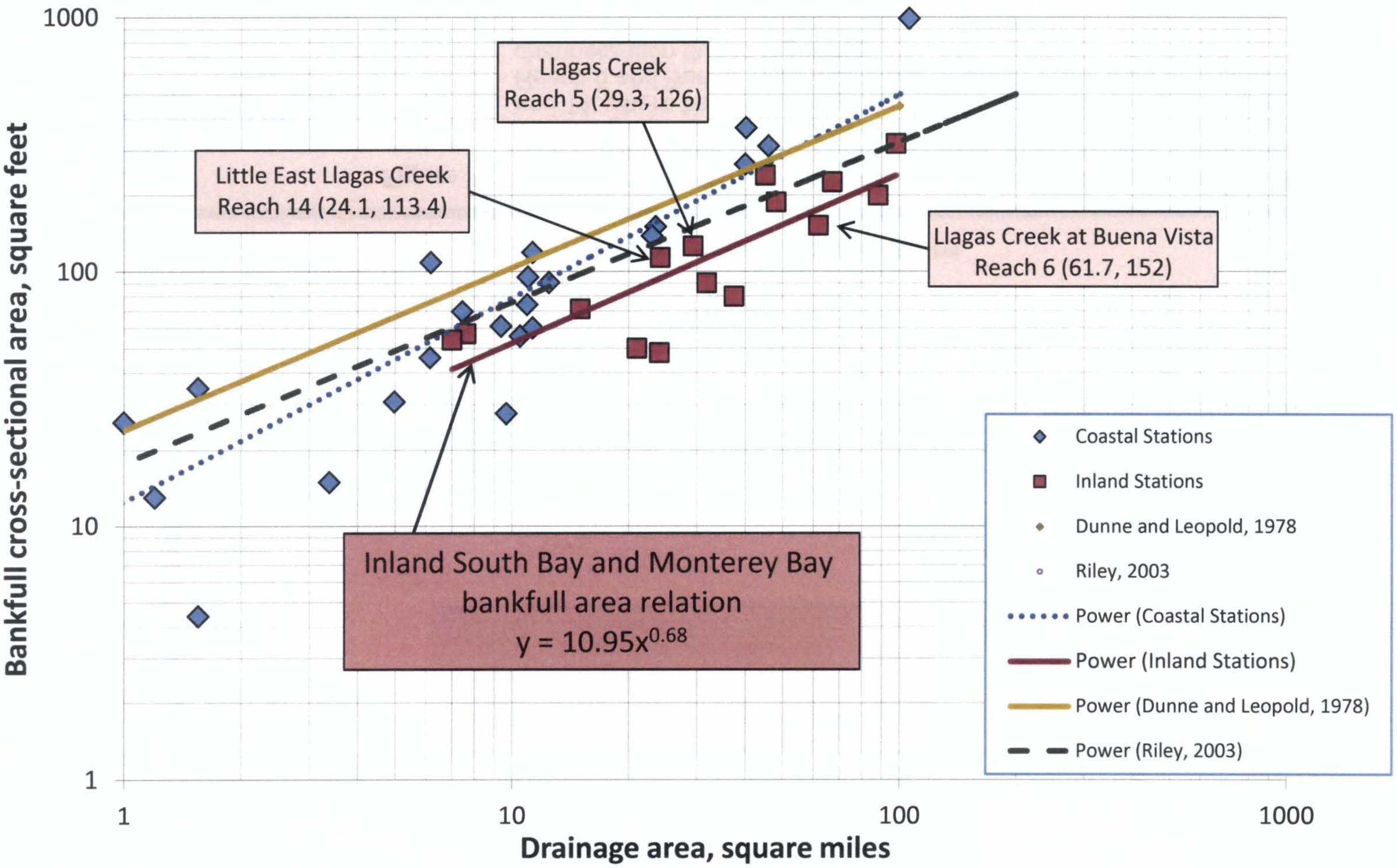

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Figure 6. Bankfull channel cross-sectional area geometry relations, San Francisco Bay Region, California. The regression equation for the Inland South Bay and Monterey Bay relation shows that streams in this region have smaller channel dimensions for the same size of watershed than those in more northern or coastal Bay Area counties due to lower rainfall and runoff rates. These smaller dimensions nevertheless reflect a larger regional pattern of similar regression slopes, but with smaller cross-sectional area per watershed area in the drier southern channels .

209164 Fig 6. Bankfull Geometry Regression Curves; XS area. Refer to Tables 1 and 2 for data.

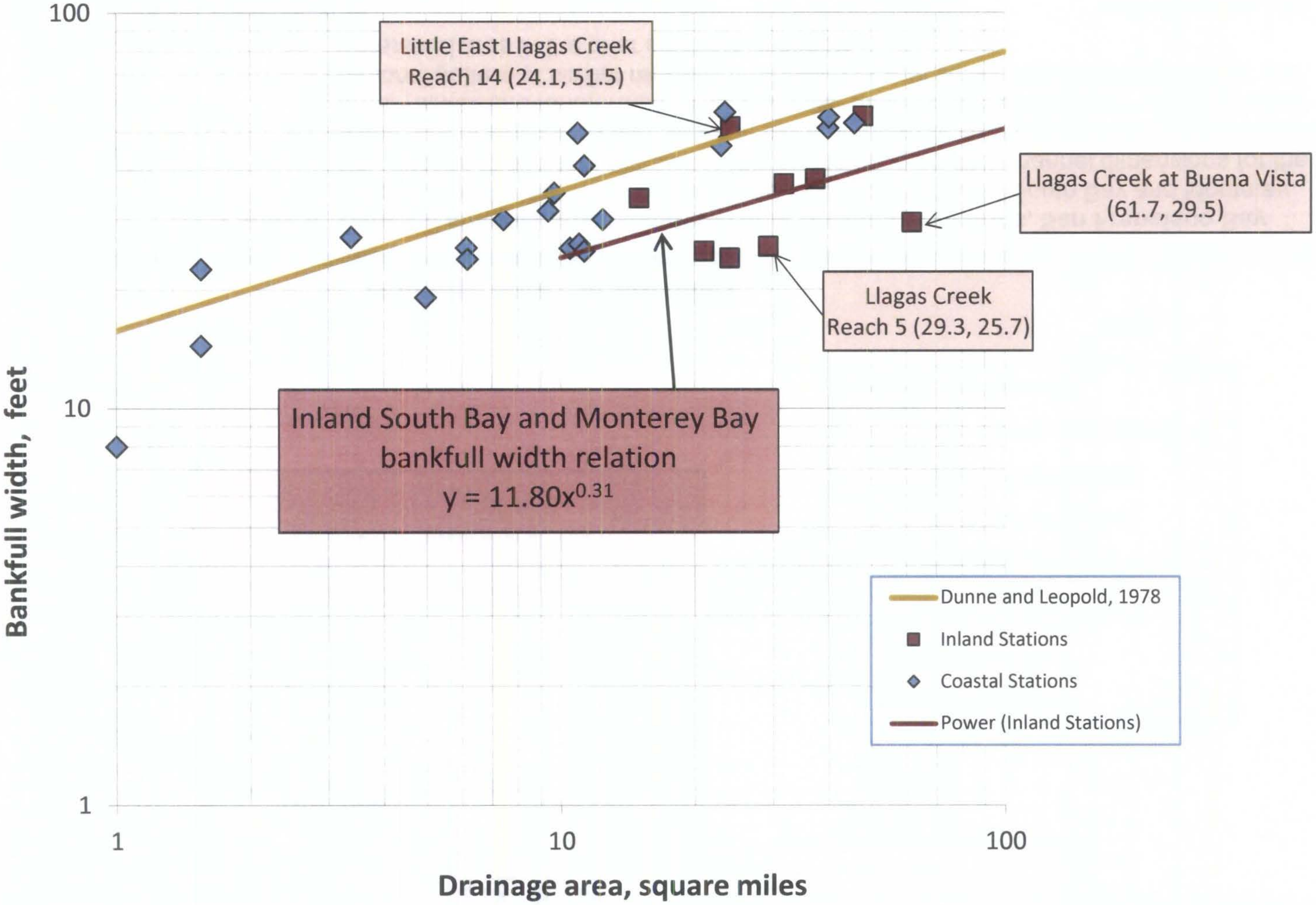

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Figure 7. **Bankfull channel width relations, San Francisco Bay Region, California.** Little East Llagas Creek Reach 14 is much wider than the other inland data points, indicating a progressively incising channel upstream of the confluence of Reaches 5 and 14, where bank instability causes an increase in channel widths. Llagas Creek Reach 5 and Buena Vista widths plot distinctly lower than predicted, a sign of channelization due to regulation.

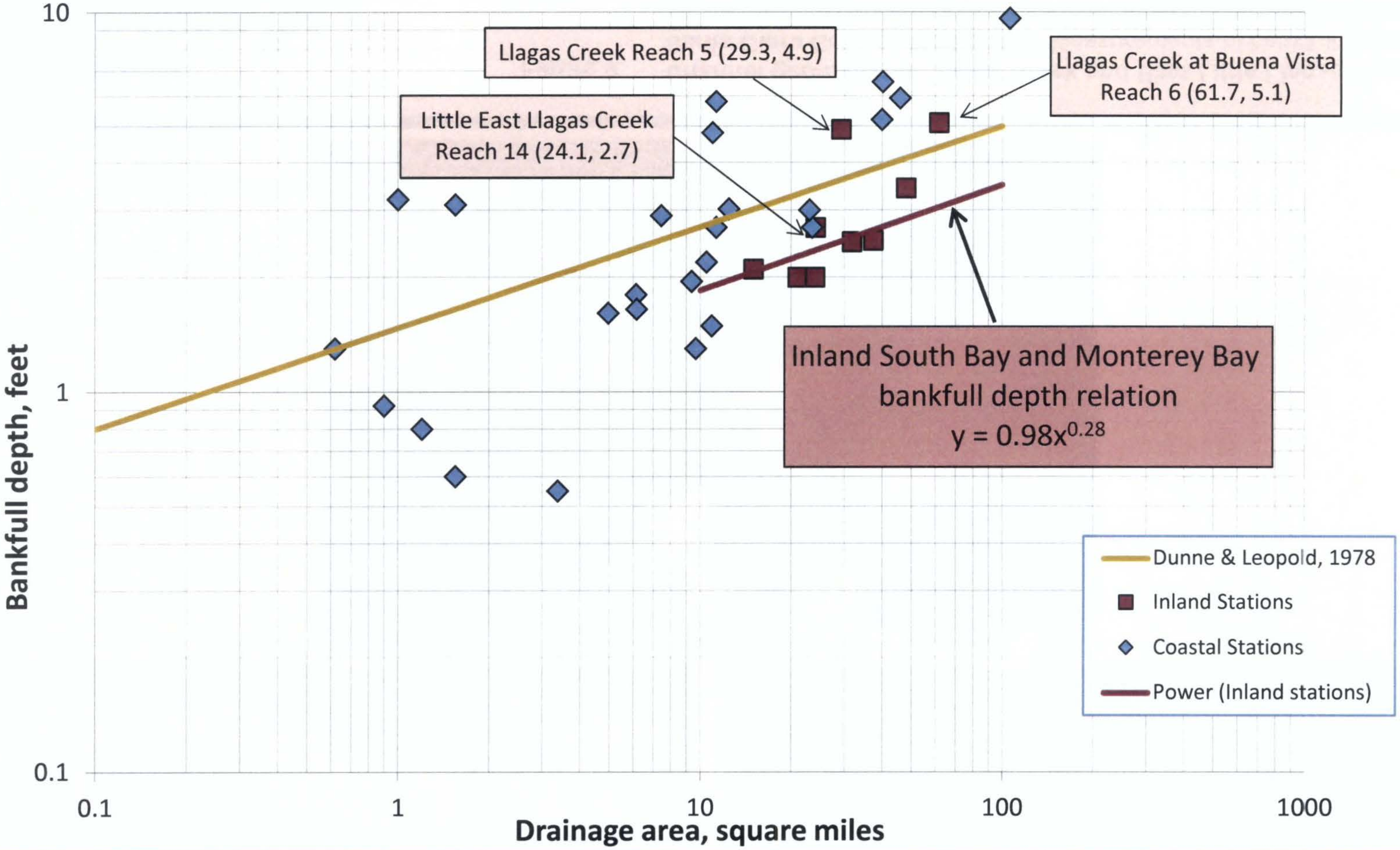

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Figure 8. Bankfull channel depth relations, San Francisco Bay Region, California. The Inland station depth values have been modified to parallel the Dunne and Leopold curve rather than fit to all data points. Llagas Creek Reaches 5 and 6 values, with significantly larger depths, were removed from the the regression. This decision was made using professional geomorphic judgement, and reflects observation of significant mainstem incision at both sites.

Fig 8. Cross-sectional depth, bankfull geometry relations. Refer to Tables 1 and 2 for data.

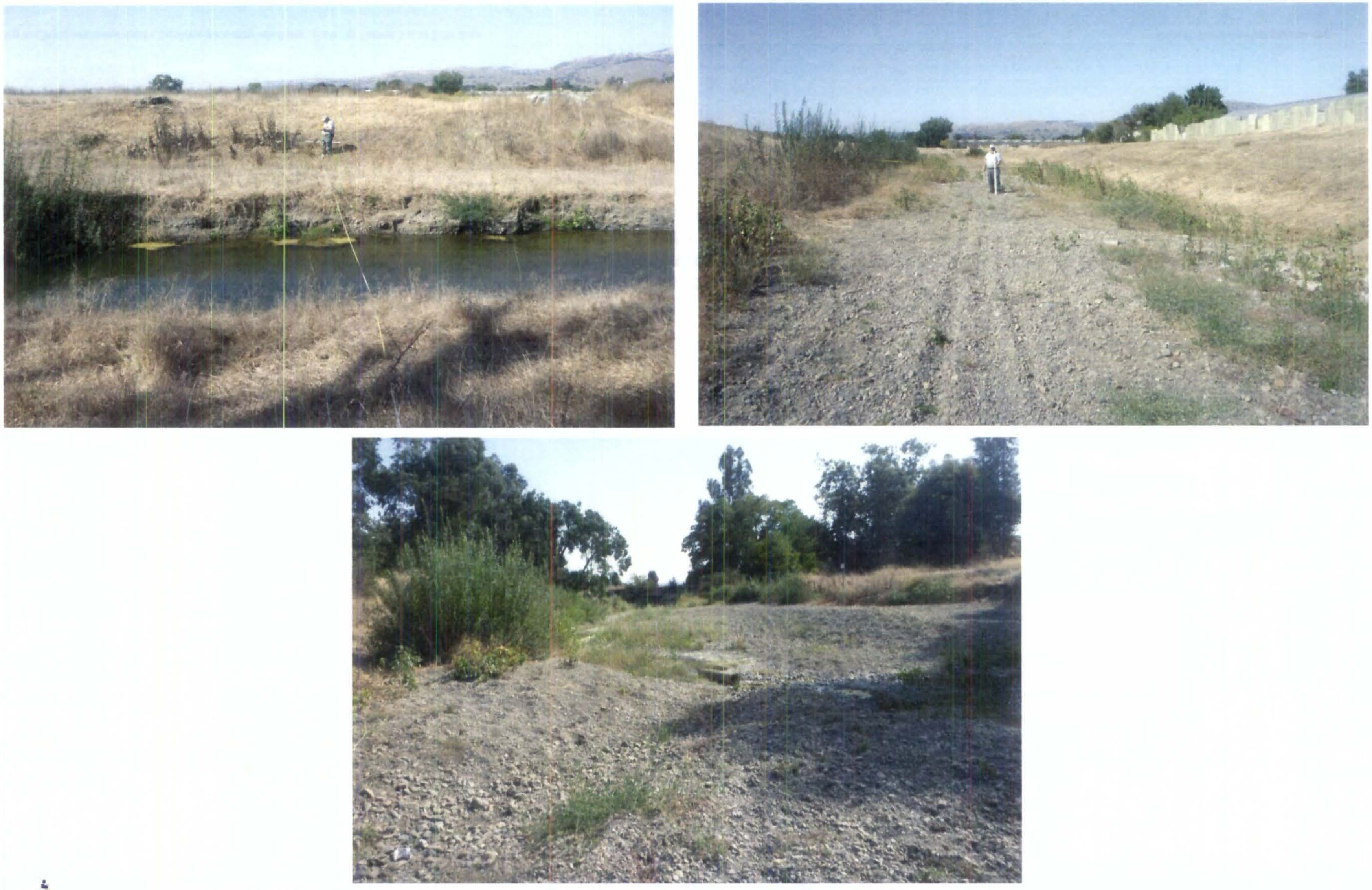

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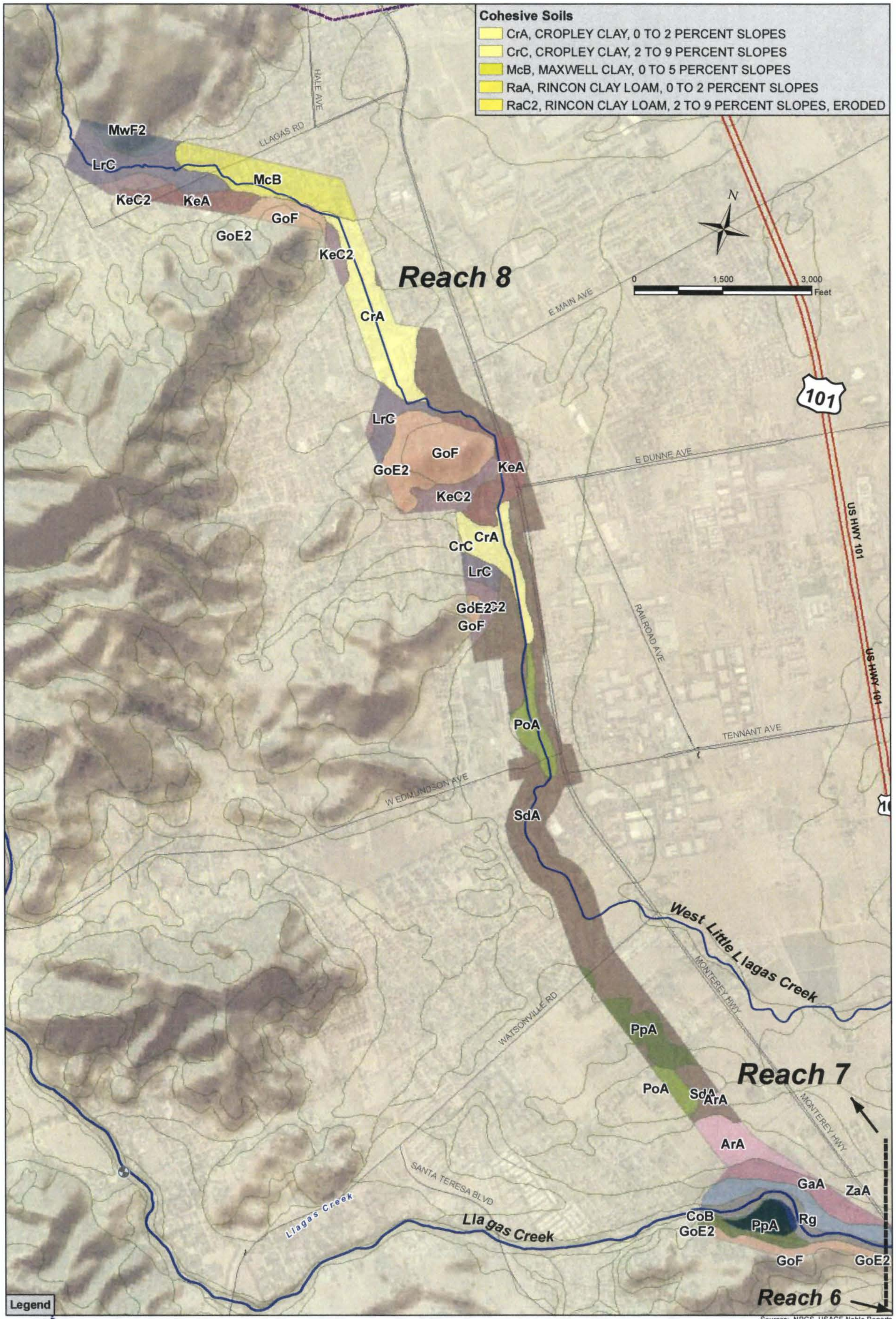
Figure 9. **Channel geometry at Llagas Creek and East Little Llagas Creek, Santa Clara County, California.** Measurements of bankfull geometry above the confluence (bottom photo) of Llagas (upper left) and East Little Llagas Creeks (upper right) collected on September 9, 2011.



Sources: NRCS, USACE Noble Reports

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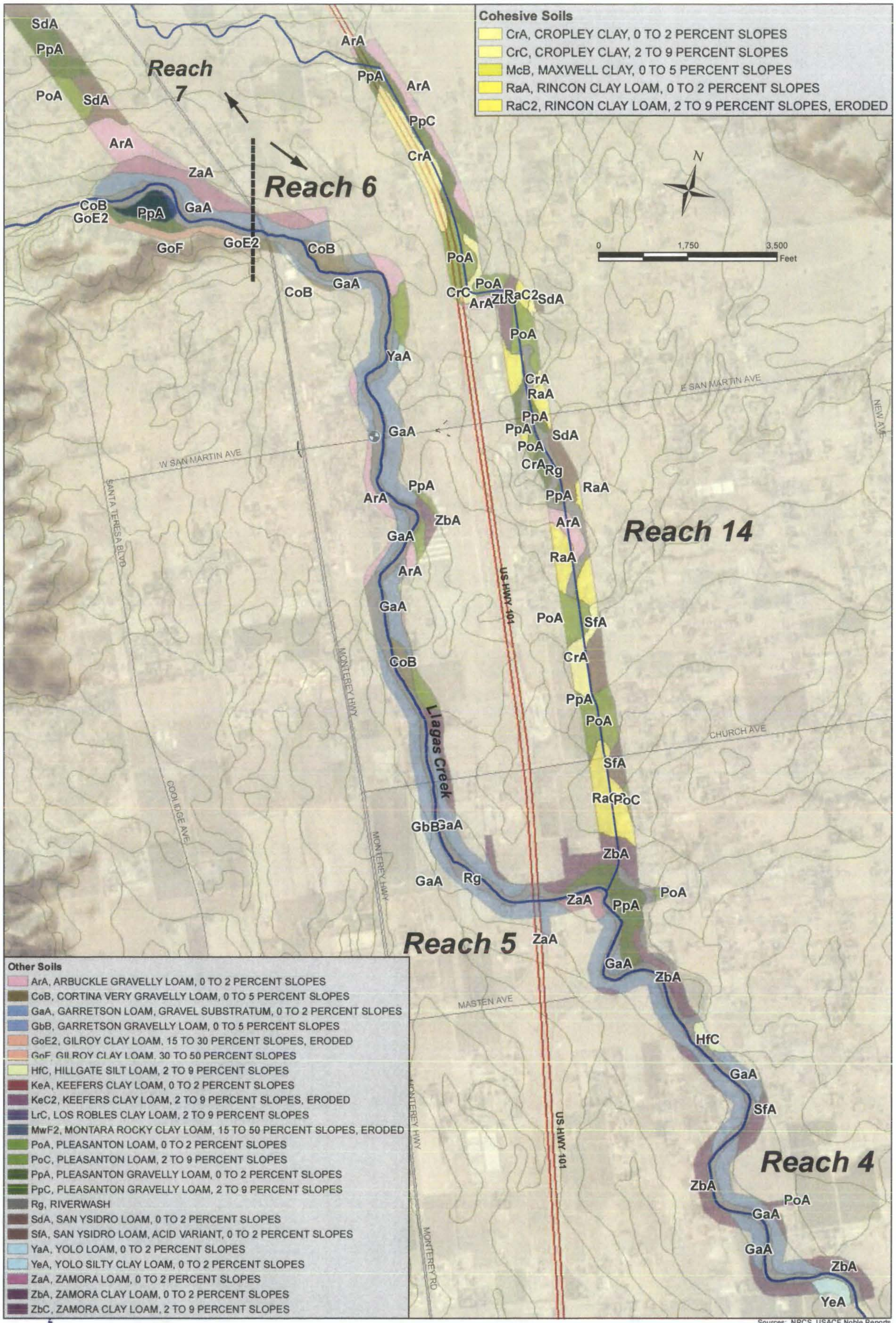
Figure 10a. Generalized soil types adjacent to reaches 7 and 8, Llagas Creek watershed, Santa Clara County, California.

209164_Llagas_reaches soils A.mxd


Cohesive Soils
CrA, CROPLEY CLAY, 0 TO 2 PERCENT SLOPES
CrC, CROPLEY CLAY, 2 TO 9 PERCENT SLOPES
McB, MAXWELL CLAY, 0 TO 5 PERCENT SLOPES
RaA, RINCON CLAY LOAM, 0 TO 2 PERCENT SLOPES
RaC2, RINCON CLAY LOAM, 2 TO 9 PERCENT SLOPES, ERODED
Reach 7
Reach 6
Reach 14
Reach 5
Reach 4
Llagas Creek
N
0
1,750
3,500
Feet
US HWY 101
MONTEREY HWY
MONTEREY RD
SANTA TERESA BLVD
COOLIDGE AVE
W SAN MARTIN AVE
E SAN MARTIN AVE
NEW AVE
CHURCH AVE
MASTEN AVE
SdA
PpA
PoA
ArA
ZaA
CoB
GoE2
GaA
GoF
PpC
CrA
CrC
ZbA
RaC2
YaA
RaA
Rg
SfA
PoC
GbB
HfC
YeA
Other Soils
ArA, ARBUCKLE GRAVELLY LOAM, 0 TO 2 PERCENT SLOPES
CoB, CORTINA VERY GRAVELLY LOAM, 0 TO 5 PERCENT SLOPES
GaA, GARRETSON LOAM, GRAVEL SUBSTRATUM, 0 TO 2 PERCENT SLOPES
GbB, GARRETSON GRAVELLY LOAM, 0 TO 5 PERCENT SLOPES
GoE2, GILROY CLAY LOAM, 15 TO 30 PERCENT SLOPES, ERODED
GoF, GILROY CLAY LOAM, 30 TO 50 PERCENT SLOPES
HfC, HILLGATE SILT LOAM, 2 TO 9 PERCENT SLOPES
KeA, KEEFERS CLAY LOAM, 0 TO 2 PERCENT SLOPES
KeC2, KEEFERS CLAY LOAM, 2 TO 9 PERCENT SLOPES, ERODED
LrC, LOS ROBLES CLAY LOAM, 2 TO 9 PERCENT SLOPES
MwF2, MONTARA ROCKY CLAY LOAM, 15 TO 50 PERCENT SLOPES, ERODED
PoA, PLEASANTON LOAM, 0 TO 2 PERCENT SLOPES
PoC, PLEASANTON LOAM, 2 TO 9 PERCENT SLOPES
PpA, PLEASANTON GRAVELLY LOAM, 0 TO 2 PERCENT SLOPES
PpC, PLEASANTON GRAVELLY LOAM, 2 TO 9 PERCENT SLOPES
Rg, RIVERWASH
SdA, SAN YSIDRO LOAM, 0 TO 2 PERCENT SLOPES
SfA, SAN YSIDRO LOAM, ACID VARIANT, 0 TO 2 PERCENT SLOPES
YaA, YOLO LOAM, 0 TO 2 PERCENT SLOPES
YeA, YOLO SILTY CLAY LOAM, 0 TO 2 PERCENT SLOPES
ZaA, ZAMORA LOAM, 0 TO 2 PERCENT SLOPES
ZbA, ZAMORA CLAY LOAM, 0 TO 2 PERCENT SLOPES
ZbC, ZAMORA CLAY LOAM, 2 TO 9 PERCENT SLOPES

Sources: NRCS, USACE Noble Reports

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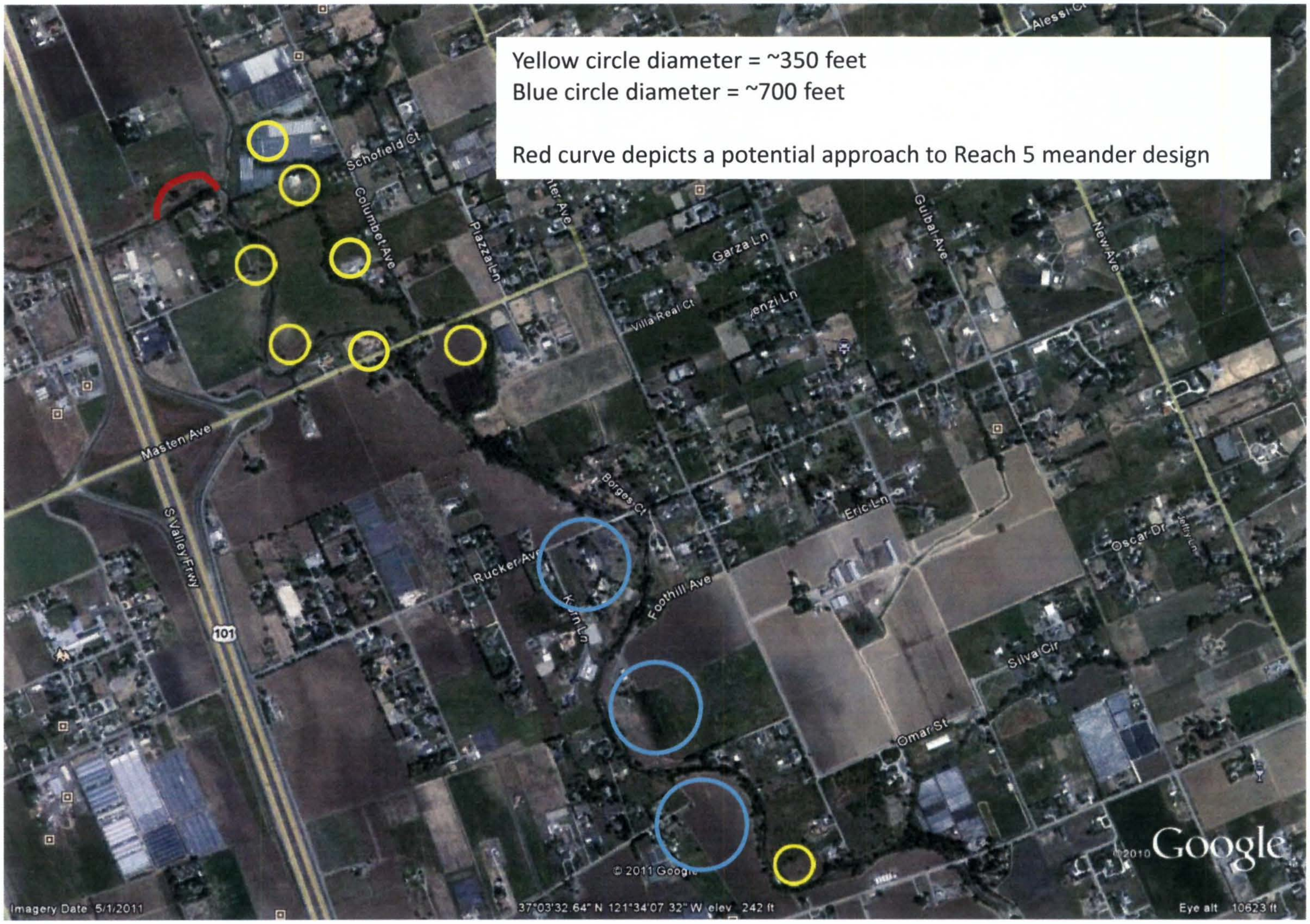
Figure 10b. Generalized soil types adjacent to reaches 4, 5, 6 and 14, Llagas Creek watershed, Santa Clara County, California.

209164_Llagas_reaches soils B.mxd



Yellow circle diameter = ~350 feet
Blue circle diameter = ~700 feet

Red curve depicts a potential approach to Reach 5 meander design

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Figure 11. Relict self-formed meander curvatures of Llagas Creek, Reach 4, Santa Clara County, California. These meanders appear to remain from the pre-agricultural valley floor, before Llagas Creek was locally straightened, and incident flows were modified by construction of Chesbro Dam. Circles with diameters of 350 feet (radius of 175 feet) have been drawn to show that numerous self-formed curves have radii in the range of 120 to 200 feet, implying that the pre-agricultural bankfull width through much of Reach 4 ranged between 50 and 65 feet. Stable bankfull widths under 2011 flows may will be slightly less, due primarily to peak attenuation at Chesbro. Other factors also influence stable bank widths.